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THE ALTERNATE CURRENT TRANSFORMER

IN THEORY AND PRACTICE.

BY

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ERRATA.

The reader is requested to make the following corrections.—

On page 452, line 15,

instead of $$B_n = \frac{2}{T}\int_0^T n \cos\frac{2\pi n t}{T}\,dt,$$

read $$B_n = \frac{2}{T}\int_0^T x \cos\frac{2\pi n t}{T}\,dt.$$

On page 487, last two lines of page, *instead of* "one or two centimetres," *read* "one or two millimetres."

On page 488, lines 7 and 8, *instead of* "all cases in which frequencies less than 200 volts," *read* "cases in which frequencies less than 200."

On page 517, formula (13),

instead of $$B^{\frac{1}{3}} = (p\,S\,N\,E\,.\,10^8)^{\frac{1}{3}},$$

read $$B^{\frac{1}{3}} = \left(\frac{E\,.\,10^8}{p\,S\,N}\right)^{\frac{1}{3}}$$

On page 527, in the Table of Iron Core Losses of Model Hedgehog 1:1 Transformer, in the last line of table, under total copper losses, *instead of* "12·5," *read* "125."

CHAPTER I.

THE HISTORICAL DEVELOPMENT OF THE INDUCTION COIL AND TRANSFORMER.

§ 1. **The Evolution of the Induction Coil.**—In following out the stages of development of the induction coil and the transformer, we find that they are no exceptions to the general law that improvements in experimental appliances advance along definite lines by a process of evolution in which rudimentary forms are successively replaced by more and more completely developed machines. We are able by a careful scrutiny of existing and pre-existing modifications to detect the ideas which at every step have impelled invention forward, and also to examine the prototypes in their relation to the final and fully developed idea. Most readers would probably consider that the proto-typical form of all modern induction coils and transformers was the iron ring with which Faraday made the initial discovery in electro-magnetic induction,* and in one sense this is of course correct, but a careful examination of the early stages of the development of the induction coil as we now possess it seems to show that it is descended in the direct line not from Faraday's ring so much as from Henry's flat spirals, and that it is these latter which are the chiefs of the clan and true ancestors of our modern coil.

Henry's claim to be an independent discoverer of the fundamental fact of electro-magnetic induction is not now disputed. In the July number of *Silliman's American Journal of Science* for 1832, Joseph Henry, then a young teacher in the Albany Academy, gave an account of the manner in which he had independently, and before receiving an account of Faraday's work performed in the previous autumn, elicited from his own great electro-magnet an induced current by wrapping round the soft iron armature certain coils of insulated wire.* In the same Paper in which he thus discloses his anticipated discovery he rendered an account of that in which he had in turn anticipated his illustrious rival by the discovery of the fact of the *self-induction* of a spiral conductor, and denoted the phenomenon by the name by which it has since been known. Simply confining himself to the bare statement of the new fact that if the poles of a small battery are joined by a wire a foot long no spark will be found on breaking the circuit, whereas if the wire be thirty or forty feet long, and particularly if it be coiled into a spiral, it gives a bright spark when so employed, Henry noted the discovery and correctly attributed the phenomenon to the induction of the circuit upon itself. Finding, however, that Faraday was following on the same line of discovery he published in the *Journal of the Franklin Institute*, in March, 1835 (Vol. XV., pp. 169-170), a brief epitome of the facts he had collected, and made mention, for the first time, of the use of the spirals of flat copper tape or ribbon, insulated and closely wound together, with which he subsequently conducted his brilliant train of discoveries on the mutual induction of circuits.

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* *See* "The Alternate Current Transformer," Vol I., p. 2.

A few months later, in the July number of *Silliman's American Journal of Science*, 1835 (Vol. XXVIII., pp. 329-331), he followed this up with a more explicit account of his investigations on the action of a spiral conductor, especially a flat tape spiral, in increasing the spark and the shock from a single cell of a galvanic battery. Using a very large single cell of very low internal resistance known as "Dr. Hare's Calorimotor," he sent the current from this through a spiral conductor formed of copper ribbon about one inch wide and from sixty to one hundred feet long, well covered with silk, and the several spires closely wound on each other. One end of the conductor being attached to one pole of the battery and the other being brought in contact with or rubbed along the rough edge of a plate of metal attached to the other end, he obtained vivid sparks at the place of contact. Moreover, he noted that if copper cylinders two inches in diameter and about five inches long were attached as handles to the ends of the spiral by supplementary wires, and if these cylinders were grasped by moistened hands, a series of sharp shocks was experienced when the end of the spiral conductor was as before drawn along the rough edge of one plate of the calorimotor. This preliminary investigation on the production of a spark and a shock from a single cell of a battery led him to make a thorough investigation of the phenomenon, in which he most fully explored the whole of the facts. These experiments he recounted in the *Transactions of the American Philosophical Society* for February, 1835 (Vol. V., pp. 223-231); and in *Silliman's American Journal of Science* for July, 1835, covering in these pages a recital of the independent investigations he made in going over the same ground as that occupied by Faraday in his Ninth series of "Electrical Researches" *On the Influences by Induction of an Electric Current on Itself*, which was sent to the Royal Society in December, 1834, and read in January, 1835. Henry's removal from Albany Academy to Princetown College created an interruption in his researches, but the news of them travelled to England, and in turn created a further wave of discovery. The subject was taken up by William Sturgeon, the inventor of the electro-magnet. Sturgeon met one day a Mr. Peaboddy, lately from the United States, in the Adelaide Gallery of Practical Science,* and this gentleman

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* *See* "Collected Scientific Writings of Professor Joseph Henry," Vol. I., p. 73; also, *Silliman's American Journal of Science*, July, 1832, Vol. XXII., pp. 403-408; also, Prof. E. N. Dickerson's "Sketch of the Life of Joseph Henry," p. 12.

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* The building, which was formerly the Adelaide Gallery of Practical Science, now survives as Gatti's restaurant in the Strand. It has many interesting electrical reminiscences connected with it. In the Adelaide Gallery Wheatstone performed his classical experiments on the "Velocity of Electricity" in 1834 (*see* "Wheatstone's Scientific Papers," p. 90). In it also Faraday performed the experiments on the Electrical Fish or Gymnotus, and established the real electrical nature of its shock in 1838 (*see* "Electrical Researches," Vol. II., p. 3).

The following extract from EDWARD WALFORD'S "Old and New London" may be of interest:—

"Adjoining the Lowther Arcade, with its entrance in Adelaide-street, is the Adelaide Gallery, originally intended as a place of amusement and instruction combined. It was first opened in the year 1830, and named after Queen Adelaide, the consort of William IV. Its varied fortunes, informed him of Henry's experiments on the production of a shock and spark from a single pair of plates in a galvanic cell. Sturgeon was at that time just engaged in launching a new venture, in the shape of his *Annals of Electricity*, a monthly journal devoted especially to electrical science; and in the first volume of this publication, he led off with a Paper "On the Electric Shock from a Single Pair of Plates," in which he gave an account of Henry's work and of his own repetition of the experiments (*Sturgeon's Annals*, Vol. I., p. 67). This was published in October, 1836. W. Sturgeon did not appear at this time to have been acquainted with Faraday's Ninth series of Electrical Researches; but after repeating most of Henry's experiments, and adding some of his own, he arrived at the conclusion that the action of the spiral conductor in creating a shock was due to the *collapse* of the magnetic lines of force

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from the day when it was opened as a temple of science down to its tranformation into a casino, are thus cleverly sketched by the late Mr. Albert Smith in his little book on 'London Life and Character':—'Some time back—dates are very dry things, so we need not care about the precise year—there existed in the neighbourhood of the Lowther Arcade an establishment called the Adelaide Gallery. It was at first devoted to the diffusion of knowledge. Clever professors were there, teaching elaborate sciences in lectures of twenty minutes each; fearful engines revolved and hissed and quivered, as the fettered steam that formed their entrails grumbled sullenly in its bondage; mice led gasping sub-aqueous lives in diving bells; clock-work steamers ticked round and round a basin perpetually to prove the efficacy of invisible paddle-wheels; and on all sides were clever machines which stray visitors were puzzled to class either as coffee-mills, water wheels, roasting jacks, or musical instruments. There were artful snares laid for giving galvanic shocks to the unwary, steam guns that turned bullets into lead sixpences against the target; and dark microscopic rooms for shaking the principles of teetotallers, by showing the wriggling abominations in a drop of the water which they were supposed daily to gulp down. Then came a transition stage in the existence of the Adelaide Gallery, at first stealthily brought about. The oxy-hydrogen light was slily applied to the comic magic lantern, and laughing gas was made instead of carbonic acid. By degrees music stole in, then wizards, and lastly talented vocal foreigners from Ethiopia and the Pyrenees. Science was driven to her wit's end for a livelihood, but she still endeavoured to appear respectable. . . . And at last all the steam-engines and waterworks were cleared away, and the Adelaide Gallery was devoted entirely to the goddess of the "twinkling feet," and called a casino. It was altered into the Marionette Theatre in 1852, and is now one of the refreshment rooms of Messrs. Gatti.'"

when the current in the coil was interrupted, and that this gave rise to a momentary self-induced current in the coil set in motion by a greater electromotive force than that of the exciting cell. Subsequently he became acquainted with Faraday's prior work on self-induction, and in a critical Paper (Sturgeon's *Annals of Electricity*, Vol. I., p. 192) he discusses Faraday's results, and with great skill experiments with a number of coils with and without iron cores, with the object of finding out how much of the "shock" was due to the iron, and how much to the wire coils. On page 283, Vol. I., of the *Annals* there is a full reprint of Henry's Paper read before the American Philosophical Society in February, 1835.

§ 2. **Page's Researches.**—The next important fact seems to have been added by Prof. C. G. Page, of Washington, in the United States, who published an account in *Silliman's American Journal of Science* for October, 1836 (Vol. XXXI., p. 137), of his researches on the self-induction of spiral conductors. Sturgeon abstracted an account of Page's work in his *Annals* (Vol. I., p. 290), and made it available for English readers. Prof. C. G. Page constructed in 1835 a spiral copper strip coil, of which the strip was one inch wide and 220ft. long, carefully insulated, and having terminal wires soldered at intervals of 55ft. This strip was rolled up into a flat spiral, and mercury cups attached to the six terminal wires.

A single cell of a Hare's calorimotor, or large copper-zinc cell, was then attached to an adjacent pair of terminals, and it was found that on breaking the battery contact sparks and shocks could be procured by touching any of the other terminals in pairs.

The difference between Henry's and Page's arrangements may be indicated by a diagram, in which for clearness the copper strip is represented as unrolled.

Let S S (Fig. 1) be Henry's copper strip coil unrolled, and let B be a galvanic cell, and H H the handles for taking the inductive shock, when the battery circuit is broken at C. In Henry's experiments the arrangement of the coil was such that the self-induction of the whole of it was employed in producing the shock when a person held the handles H H.

In Page's arrangement the strip with its six or seven contacts is represented by S S (Fig. 2), and the cell or battery was applied to the terminals 1 and 2. Page found that severe shocks could be obtained by taking hold of metal handles attached to the terminals 7 and 3, or 6 and 5, or 7 and 6, when the battery circuit was broken at C. By making the break and make of contact by a rapidly revolving spur wheel he

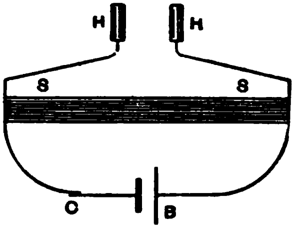

FIG. 1.—Diagram representing Henry's Ribbon Coil unrolled.

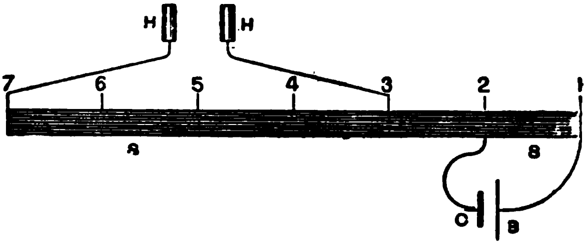

FIG. 2.—Diagram representing Page's Ribbon Coil unrolled.

got a succession of sparks from a portion of the strip not included between the battery terminal. In place of a spur wheel he also made and broke contact rapidly by dragging one end of the battery wire over a file or rasp in contact with the plate of the battery.

On page 294 of Vol. I. of the *Annals* Sturgeon explained Page's experiment correctly as due to the induction of one part of the coil on the other. Page really made the first experiment in *auto-induction*, and showed that different parts of the same conductor might act as primary and secondary circuits to each other if in contiguity.

§3. Callan's Induction Apparatus.—We then come to an important contribution by the Rev. N. J. Callan, of Maynooth College. This investigator followed up with great interest and success the researches of Faraday, Henry, Page, and W. Sturgeon; and on page 295 of Sturgeon's *Annals of Electricity*, Vol. I., we have a Paper by him, written in 1836, "On the best method of making an electro-magnet for electrical purposes, and on the vast superiority of the electric power of the electro-magnet over the electric power of the common magneto-electric machine."

In this Paper Callan describes the construction of an electromagnet with *two separate insulated wires, one thick and the other thin*, wound on the iron core together. He first coiled on a long and thick horseshoe-shaped bar of iron a very *thick copper wire* covered with silk or cotton, and securely over this a very long *thin iron wire*, also insulated with cotton, and one end, viz., the inner end, of the iron wire was joined to the outer end of the copper circuit. In his first magnet the copper wire consisted of a wire 50ft. long and one-twelfth of an inch in diameter, and the iron wire was 1,300ft. long and one-fortieth of an inch in diameter.

He sent a current from a battery of one or two pairs of plates through the thick copper wire, and attached metallic handles to the ends of the iron wire for the purpose of taking a shock, and then on making and breaking the circuit of the battery rapidly he got severe shocks from the iron wire circuit. Here we have the first description that exists of an induction coil with a short thick and a long thin wire upon it; but the peculiarity of it was that the end of the secondary or thin wire was joined to the end of the thick wire, so that they formed one circuit wound all in the same direction upon the magnet. Callan's experiment was, therefore, an extension of Page's, and this last, again, was an improvement on Henry's apparatus. Callan followed up this Paper by another dated June 14, 1836, published in Sturgeon's *Annals*, Vol. I., p. 376, being "A description of the most powerful electro-magnet yet constructed."

He had forged an iron bar 2½ inches in diameter, 13 feet long, and bent into a horseshoe. It weighed 15 stone. Four hundred and ninety feet of insulated copper wire, one-sixth of an inch in diameter, were wound on it in one layer, and over this a thin insulated copper wire 10,000 feet long and one-fortieth of an inch in diameter; and one end of the thin wire was soldered to one end of the thick wire, so that the whole length of the two wires formed a single circuit, wound all in the same direction on the big horseshoe. The current from 20 large Callan cells (iron cells), or from a Wollaston battery of 280 pairs of plates, was passed through the thick copper wire circuit alone, and rapidly interrupted by an apparatus Callan called a *repeater* (*see* Fig. 3). Wires were soldered to the extremities of the fine wire circuit to receive the induced current. Provided with this formidable apparatus, the inventor proceeded to perform striking experiments with the induced currents. "When by means of an *electro-magnetic repeater* a rapid succession of secondary currents was induced in the fine wire, and passed between charcoal points attached to the ends of the secondary circuit, they were slightly ignited." The shock, as can be imagined, was exceedingly severe, and the ardent experimentalist proceeded to pass from this germinal experiment in the production of an arc light by means of a transformer to an experiment in *electrocution*. For he adds: "Although the igniting power of the electric current produced in the long coil of thin wire was very feeble, its intensity was exceedingly great. When it (the secondary current) was passed through the body of a large fowl instant death was produced." This

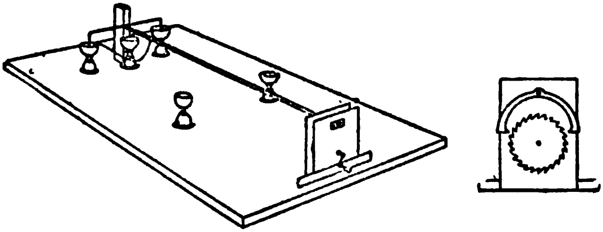

FIG. 3.—Callan's Electro-Magnetic Repeater, or Vibrating Contact Breaker.

magnet, or one like it, was sent by Callan to Mr. Sturgeon, and by him exhibited to the London Electrical Society at a meeting held on August 5, 1837, and members and visitors enjoyed powerful shocks from the secondary wire of this electro-magnetic apparatus.

§ 4. **Sturgeon's Coil.**—In Sturgeon's *Annals of Electricity*, Vol. I., p. 418, there is a mention of the meeting of the London Electrical Society held on August 5, 1837, when Sturgeon read a paper on "Secondary Electric Currents," illustrated by a powerful double-wire horseshoe electro-magnet which had been presented to him by Prof. Callan, of the R.C. College, Maynooth. This paper or lecture stimulated several minds, and particularly that of Sturgeon himself. On page 470 of the *Annals*, Vol. I., we have another Paper by him, on "An Experimental Investigation of the Influence of Electrical Currents on Soft Iron as regards the thickness of metal requisite for the full display of Magnetic Action, and how far these pieces of iron are available for Practical Purposes." He constructed a double-wire helix on Callan's plan. He wound on a wooden bobbin a naked copper wire insulated with sealing-wax varnish. One wire was a copper bell wire, 260 feet long, forming the inner or lower coil; and the upper or outer coil was a thinner copper wire, 1,300 feet long. The end of the fine wire was soldered to one end of the thick wire, so that it made one continuous

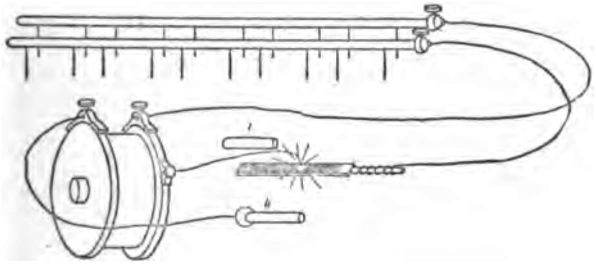

FIG. 4.—Sturgeon's Induction Coil with Wooden Core.

Contact breaker at terminal *l*, consisting of a file rubbed by the wire end. Free terminal, provided with handle *k*.

conductor, wound all the same way on the bobbin. The reel, or bobbin, was of wood, two inches long between the cheeks. (*See* Fig. 4.) Strips of silk were interposed between the layers of wire. Hence, Sturgeon's coil was a short, wide coil, wound on a hollow wooden core, and not like Callan's magnet, which was long and thin. Sturgeon applied to his coils a break-and-make arrangement, consisting of a wire dipping in a mercury cup in one case and of a notched zinc disc in the other. (*See* Figs. 5 and 6.) The mercury cup-break was worked by a revolving cam and lever, and gave about 36 breaks per second when the cam was turned round by a winch. With the zinc disc he got 540 breaks per second. He put a *solid* iron core in the bobbin, and he was delighted to find that he got powerful shocks from the secondary circuit when the current from one or two cells was interrupted in the primary. He then made a very curious observation. He found that with the solid iron core the shock was much diminished in amount when the revolving contact-breaker went above a certain speed. After some trials he substituted a bundle of fine iron wires for the solid core, and he got very much better results. He draws attention to the fact that (*Annals*, Vol. I., p. 481) Prof. G. H. Bachhoffner had

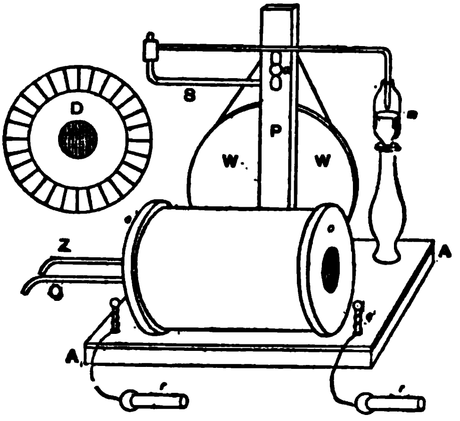

FIG 5.—Sturgeon's Induction Coil.

Z and C, wires from battery. *o o*, coil. A A, base of coil. W W, driving wheel for contact breaker. *a*, cam lifting a wire attached to arm S. *m*, a mercury contact.

tried a divided iron core about a fortnight before he had with one of Sturgeon's own coils, which he had lent him. Bachhoffner observed that a bundle of fine iron wires used as a core in Sturgeon's coil gave far better shocks than when a solid iron bar was employed. We must therefore credit Bachhoffner with being the first to recognise the value of a divided iron core. W. Sturgeon noted that a rolled-up sheet of tinned iron put in as a core increased the shocking power in an extraordinary degree beyond that obtained when a solid core was used, and that with a bundle of fine iron wires as a core the shocks were still more increased. Sturgeon claimed that his coil was an advance on Callan's, and certainly when we regard the sketch of Sturgeon's first coil, we see that he gave to the appliance practically the general form which it has retained ever since. This coil of Sturgeon's was exhibited to the London Electrical Society in August, 1837.

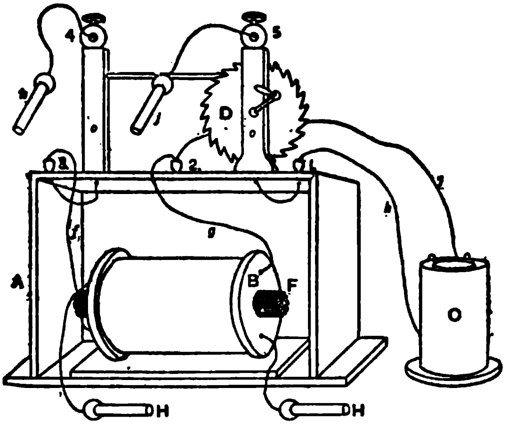

FIG. 6.—Sturgeon's First Induction Coil.

A, box containing coil. B, induction coil. C, battery. D, zinc disc contact breaker. F, iron core. H H, handles on secondary. *h* and *i*, wires from battery to contact cups 1 and 2. 4 and 5, terminals. *k* and *j*, handles.

§ 5. Callan's Coils with Separate Circuits.—We come next to another important Paper by Callan, dated September 11, 1837, printed in Vol. I., p. 491, of Sturgeon's *Annals of Electricity*.

"On a Method of Connecting Electro-magnets so as to Combine their Electric Powers, and on the Application of Electro-magnetism to the Working of Machines."

Callan wound on each of two iron bars a couple of wires, first a copper wire one-twelfth of an inch in diameter put on in one layer, and second, a copper wire one-ninetieth of an inch in diameter and 150ft. long, wound over the first. Each wire was carefully insulated both from itself as well as from the iron and the other wire. It is clear from the description which follows that in making these two induction coils Callan did *not join* the end of the secondary wires to the end of the primaries, but left the secondary distinct and insulated from the primary. He then *joined the primaries of these two induction coils in parallel* on a large galvanic cell, and the secondary coils he joined in series, and he obtained from the secondaries in series a shock greatly in excess of that which he obtained from either of them separately. He points out that the secondaries must be so united that the electromotive forces in each are added and not opposed to each other, and he surmises that if a hundred such induction coils could be arranged with secondaries in series and primaries in parallel on a very large quantity battery, it would be possible to have a shock equal to that of 100,000 or 200,000 single cells.

On page 493 (*Annals*, Vol. I.) he says:—"In making electro-magnets which are to be connected for the purpose of obtaining increased electric intensity, care must be taken *not to solder* the thin wire to the thick wire of the magnet, but to leave both ends of the thin wires projecting."

In a note he recommends that for lecture purposes the thick wire coil and the thin wire coil should be wound on separate bobbins, the thick wire bobbin being made to slide inside the thin wire bobbin; and he says that such a pair of separate coils was given by him to Mr. Cottam, the secretary of the Manchester Mechanics' Institute, during the lecture he gave there. Hence it is to Callan that we owe this simple piece of apparatus, now found in every physical laboratory, and it is to him that we are indebted for an induction coil having two separate wires, one thick and the other thin, used as an induction coil. Furthermore, he says that about four months before writing this Paper he coiled on a cylinder of wood (hollow) about 10 feet of covered copper wire, one-eighth of an inch in diameter, and over this 200ft. of very thin-covered wire, and an iron bar was put into the hollow of the bobbin. With 20 pairs of plates (*i.e.*, cells) on the primary, he got severe shocks even without the iron core, and when the core was put in he got a shock even on making the contact with the battery.

§ 6. **Bachhoffner's Divided Core.**—A little later in the first volume of Sturgeon's *Annals of Electricity* we reach a Paper by a Mr. E. M. Clarke, on an induction coil (*see* Fig. 7), for giving shocks with a single pair of plates. There is nothing more in this than a description of a Callan's or Sturgeon's coil. The secondary wire was one ninety-second of an inch in diameter, and the contact breaker was a Barker's wheel, or copper star, revolving so that the tips of its spokes just dipped in mercury in a bottle (*see* Fig. 8).

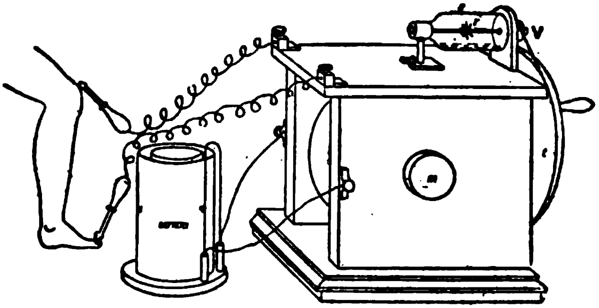

FIG. 7.—Clarke's Induction Coil.

m, core of coil. *t*, driving wheel of contact breaker. V, driven pulley. *r*, star wheel breaking contact with mercury in vessel *s*.

Some time previously Mr. Barker had invented this device for interrupting a current. Mr. E. M. Clarke was a philosophical instrument maker, having a shop in the Lowther Arcade, and his memory is also handed down to us as an improver of Pixii's magneto-electric machine. Mr. Sturgeon comments on Clarke's Paper, and, for appropriating without sufficient acknowledgment Mr. Barker's wheel and his own coil, he gives Mr. Clarke, of 11, Lowther Arcade, a dignified rebuke. Various improvers having been given the clue, took up the manufacture of induction coils. On page 205 of the *Annals of Electricity*, Vol. II., a Mr. Nesbit sends a description of a coil (*see* Fig. 9); it had a revolving ratchet wheel as a contact breaker, a primary coil, consisting of 400ft. of thick wire, and a secondary of 1,700ft. of thin wire, and as a core a bundle of very fine iron wire. This description is dated February 10, 1838. This coil gave very severe shocks when the primary was excited, with one cell of half a square foot of active surface. Nesbit put oil on his break to reduce the noise and check the spark. Four days later, on February 14, 1838, Prof. G. H. Bachhoffner has a description of a coil

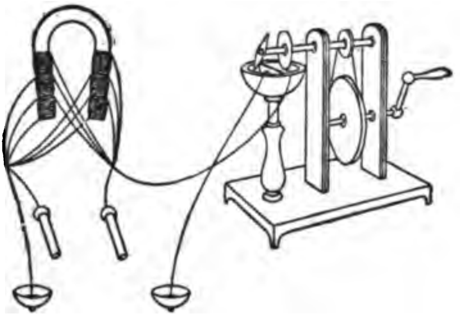

FIG. 8.—Barker's Revolving Contact Breaker, or Mercury Break.

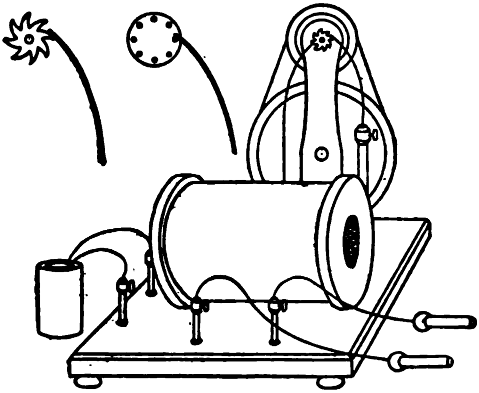

FIG. 9.—Nesbit's Induction Coil.

which he made with two separate insulated copper wires and a *core of insulated iron wires*, and he notes that if the core of fine iron wires is enclosed in a tinplate tube it ceases to act as a divided core, and becomes no better than a solid core. He claims the original suggestion of using a divided iron core, and it appears from what he says that at first he used lengths of cotton-covered iron wires in a bundle as a core.

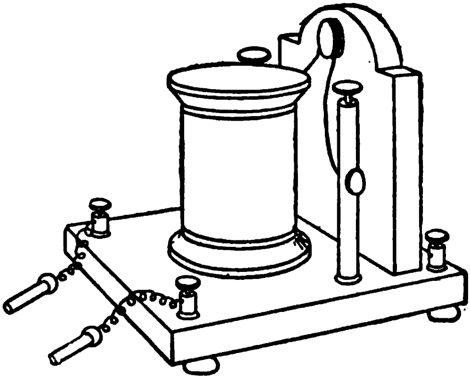

FIG. 10.—Uriah Clarke's Coil. (Side elevation.)

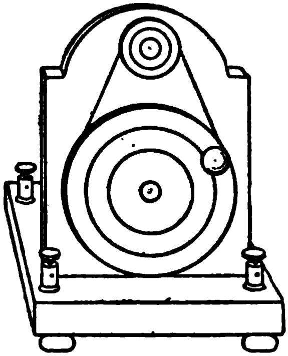

FIG. 11.—Uriah Clarke's Coil. (Back view.)

Bachhoffner refers also to a self-acting contact breaker which he put on one of his coils, and which he says was made by Mr. Neeve, of 11, Great St. Andrew's-street, Seven Dials, who made for him this magnetic contact breaker greatly superior to the spur wheel of Barker or the notched disc of Sturgeon, both of which required to be actuated by hand.

Following on these researches of Sturgeon and others, numerous investigators introduced successive smaller improvements into the construction of induction coils. Uriah Clarke, of Leicester, in June, 1838, sent to Sturgeon a description of an induction coil, in which the bobbin was placed vertically (*see* Figs. 10 and 11), and which has since been a not unusual arrangement for medical coils. In Uriah Clarke's coil a primary wire of copper, $\frac{1}{16}$in. in diameter, 40 yards long, was employed, and a secondary coil of 300 yards of very fine copper wire, also a "break" consisting of a brass wheel, having on its circumference wooden pegs, and which made and broke contact with a spring of brass resting against it. Sometimes a steel wheel with a milled edge was employed for the same purpose.

§ 7. Callan's Further Researches.—In the *Philosophical Magazine* for December, 1836, Prof. N. J. Callan made further mention of his auto-induction coils, giving also a description of an improved form of galvanic battery. He wound, on an iron bar about two feet long and an inch thick, two coils of insulated wire, each about 200ft. long. These insulated wires were joined together in series, and the extremities of one wire were put in connection with a battery of 14 cells; on taking hold of the ends of the whole length of 400ft. of wire and breaking the battery circuit, a very sharp shock was felt. He concluded that if about 2,000ft. of wire were so coiled on a bar, and the first 200ft. of this wire connected to a battery, a still greater shock would be received if the ends of the whole 2,000ft. were touched, and the battery contact broken. Twenty-one years afterwards he returned again to the subject of induction apparatus, and in a long Paper, communicated to the British Association at its Dublin meeting in 1857, and reprinted in the *Philosophical Magazine* for November, 1857, Callan described many experiments he had made in his efforts to improve the induction coil and exalt its power. Referring first to the induction coil made at Maynooth College in 1836, and to one like it sent to Mr. Sturgeon in the summer of

1837, he establishes his claims to priority in the matter of the invention of an induction coil, having two *separate* wires, one thick and the other thin, by means of which a *quantity* current could be made to produce an *intensity* current. This 1857 Paper is occupied chiefly in advocating the use of an induction coil, with a secondary circuit made of insulated iron wire, and such a coil he showed to the British Association, in which the secondary circuit consisted of 21,000ft. of iron wire, about ·01in. diameter. His arrangement apparently consisted in using a secondary circuit of insulated iron wire rolled up tightly into a cylindrical form, and which formed not only the secondary circuit, but also the iron core of the primary. The primary circuit, consisting of insulated copper wire, was wound over and outside of the iron wire secondary, and the secondary circuit thus fulfilled at once the functions of core and secondary circuit. In one form of coil described the circuits were alternately overlaid. First an iron wire secondary circuit, then a copper wire primary; then over this another iron wire secondary, and a further copper wire primary. The primary circuits were to be joined in series, and the iron wire secondaries in parallel, with the object of obtaining "considerable quantity" in the secondary currents. It is suggested that in this way it would be possible to procure current enough to operate an arc light between carbon poles. One form of induction coil suggested consisted of an iron wire secondary coil wound up tightly into a helix; and on this, considered as an iron core, the copper wire primary was wound; over this copper circuit another iron wire circuit was coiled, and the two iron wire circuits were joined up in series, so that the copper wire primary acted inductively on both, and generated induced currents in each in the same direction. Reasons are given in this Paper which led the writer to consider that this insulated iron wire secondary circuit had advantages over a secondary circuit of copper wire, and an independent longitudinally divided iron core, as introduced by Bachhoffner. Callan explained with great clearness that the principle of joining together the secondary circuits of a number of coils in parallel is the right method to adopt to obtain a secondary current of sufficient strength and electromotive force to produce an arc light, and he may, therefore, be credited with the knowledge at that date of the mode of adding up either the electromotive forces or the currents in the secondary circuits of a number of distinct induction coils. It is not quite equally clear whether he ever arranged his coils with primary circuits in parallel also. The same Paper also contains suggestions as to mode of manufacture of condensers for induction coils, and certain advantages are claimed for condensers made of iron plates rather than of tinfoil sheets. Callan's mode of insulating the wires of his coils was ingenious. He dragged the bare iron or copper wire through a hot bath of melted resin and beeswax, and this, when set, formed a highly insulating and sufficiently flexible varnish on the wire, which appears to have rendered silk or cotton covering unnecessary. The secondary circuits were wound on the plan, previously suggested by Poggendorff, of

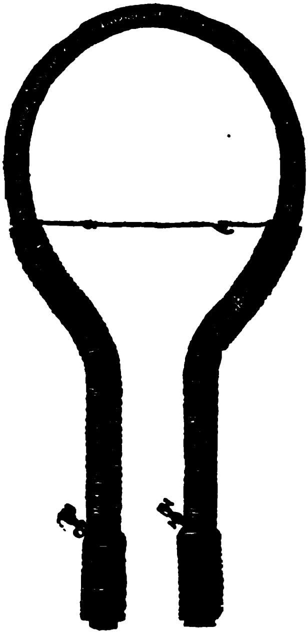

FIG. 12.—Dr. Callan's First Induction Coil (1836), with thick and thin wire Circuits.
Still preserved at Maynooth College.

building up the secondary circuit of flat or vertical coils, so connected that no contiguous parts of the wire were at great differences of potential when the coil was in action.

Prof. Francis Lennon has given* the following details of the remains of Prof. Callan's apparatus, which are still preserved at Maynooth College as valuable relics. The large electromagnet constructed by Callan in 1836, consisting of a horse-shoe of iron, about 13ft. in length, and weighing 210lb., is still in existence (*see* Fig. 12), but it has been deprived in course of time of one of its circuits, so that it now remains as a simple and not a compound electromagnet. A somewhat smaller horse-shoe magnet, constructed by him on the same principle, with two wire coils, one thick and one thin, was the one presented to Mr. Sturgeon. In the Physical Laboratory at Maynooth also exists one of Callan's Electromagnetic "Repeaters," which was one of the first rapid contact breakers ever made.

§ 8. **Callan's Great Induction Coil.**—The most valuable relic is, however, the large induction coil, which may be regarded as the completion of Dr. Callan's labours. Although constructed 30 years ago, it is still one of the largest coils in existence. The representation of it in Fig. 13 is from a photograph recently made. The core is a cylindrical bundle of annealed iron wires 42in. in length, and 3·5in. in diameter. The thickness of each wire is $\frac{3}{16}$in. The primary coil is a copper wire, ·25in. in diameter, covered with cotton thread, and wound in three layers. For insulation the primary coil is covered with several layers of thin sheet gutta-percha, cemented by a paste, formed by dissolving gutta-percha, resin, and wax in boiling oil. The secondary coil is of *iron* wire ·01in. diameter, and consists of three separate coils or rings. The inner diameter of each coil or ring is 5·75in., and the outer diameter is 21in. Two of the rings are 3in. in thickness, and one is 4in. The rings are so arranged on the primary coil as to divide its entire length into four equal parts, the planes of the rings being perpendicular to the axis of the coil. In each ring both ends of the wire are left projecting, so that the separate coils can be joined in series or in parallel. The contact breaker is an automatic mercury break, worked from one extremity of the core. Two condensers, so arranged that they can be used together or separately, serve to reduce the spark at the break. With six cells of the Maynooth or cast iron battery, sparks 15in. long in air can be still obtained, the rings or secondary coils being joined in series. Prof. Gerald Molloy states* that the construction of this coil was commenced by Dr. Callan some years before his death, which occurred in January, 1864, and that it was then left in an unfinished condition. It was probably his intention to add more secondary coils to it. It remained one of the most powerful coils down to the time of the construction of Mr. Apps' large coils for the Polytechnic and for Mr. Spottiswoode. A long Paper by Dr. Callan on the induction apparatus, describing his latest researches, is printed in the *Philosophical Magazine* for 1857, Vol. XIV., 4th series, p. 323. This Paper is full of valuable suggestions and facts.

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* See *Electrician*, March 6, 1891, Vol. XXVI., p. 554.

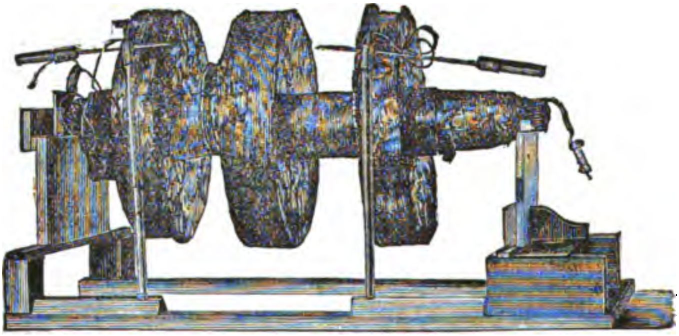

FIG. 13.—Dr. Callan's Large Induction Coil completed in 1863. Still preserved at Maynooth College.

A description of the large induction coil, and experiments with it, will be found in the *Philosophical Magazine* for June, 1863 (Vol. XXV., Series 5, p. 413). Dr. Callan says that about three years and a-half before the date of writing he made an induction coil of considerable power. The secondary coil was of iron wire, No. 34 gauge, and consisted of three parts, two of which were each about two and a-half inches, and the third three inches long. The entire length of the secondary coil was about eight inches, and it contained 150,000ft. of secondary wire. He used thin sheet gutta-percha in insulating the layers of wire. The primary coil was nearly three feet long, and the soft iron wire core three feet six inches long. This long primary coil was probably intended to be overlaid with more secondary wire, and as left at Dr. Callan's death the coil was incomplete. With three cells of the Maynooth battery this coil would give sparks 15in. in length.

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* See *Electrician*, February 13, 1891, Vol. XXVI., p. 465.

Dr. Callan discovered that an increase in length in the spark is produced by connecting a large plate of any metal to the negative terminal of the coil, and that, in order to get the longest spark, the outer end of the secondary coil should be positive, and the inner end the negative. He states (see *Philosophical Magazine*, June, 1863) that when a pointed wire is connected with the positive end of the secondary a plate connected with the negative end lengthens the spark considerably, but when the point is connected to the negative end and the plate to the positive one the sparks are much shorter. Sparks 15in. long, when the first arrangement is made, are reduced to 11in. with the second. Sparks did not pass at all between positive plate and negative point until the plate was brought within eight and a-half inches from the point.

A ball, three inches in diameter, connected to the positive terminal shortens the spark as much as a 12-in. plate. He noted also that sparks from a positive point to a negative plate never went to the circumference of the plate, and scarcely ever struck the plate at a greater distance from the centre than three inches. But sparks between a negative point and positive plate always went to the circumference until the plate was brought to within two and a-half or three inches of the point; even when a rectangular plate 20in. by 28in. was used as the positive terminal the sparks flew to the edge of the plate.

§ 9. **C. G. Page's Researches in Electro-Magnetism.**—Very nearly at the same time that Prof. Callan, of Maynooth, was assiduously engaged in England in experimental inquiries on the induction coil, Dr. C. G. Page, at Salem and at Washington, in the United States, prosecuted with the greatest zeal and ingenuity similar researches on the other side of the Atlantic. Reference has already been made to his experiments with the ribbon coils of Henry, and which are described in *Silliman's American Journal of Science*, Vol. XXXI., for 1837, in a Paper dated Salem, May 11th, 1836, and entitled "Method of Increasing Shocks, and Experiments with Prof. Henry's Apparatus for obtaining Sparks and Shocks from the Calorimeter." In a second Paper, dated April 24, 1837, Page describes the construction of a large auto-induction ribbon coil, such as has already been described in § 2, which he now calls a "Dynamic Multiplier." This last coil consisted of a single ribbon of copper, 320ft. in length and one inch in width, wound into a flat spiral, the successive turns being insulated with strips of varnished cotton cloth. It had ten mercury cups soldered to the strip at various distances. With this apparatus he repeated all his former experiments on a larger scale. At this stage Page made an important contribution to the subject by inventing various forms of self-acting contact breakers to interrupt the primary current. One of the first of these (made in 1837) was a copper spur, or star wheel, the points of which just dipped into mercury contained in a little gutter or excavation in the base board which supported the wheel. He made this self-acting by placing a horse-shoe magnet so that its poles lay on opposite sides of the wheel, as in the experiment known as Barlow's revolving spur wheel. The electro-magnetic action of the radial current in the wheel on the fixed magnetic field caused rapid rotation of the copper spur wheel, and, hence, interruption of the current, as the tips of the stellate projections of the wheel passed into and out of the mercury. He found this arrangement to answer well for interrupting a current when powerful currents were used. Such an arrangement, however, failed with feebler currents, and he accordingly devised a rocking magnet interrupter, which he describes in this same Paper, published in 1837, and which was afterwards reproduced almost identically by Golding Bird as his own invention in 1838 (*see* Golding Bird, *Phil. Mag.*, Vol. XII., 1838). Page's contact breaker and Bird's reproduction of it consisted of a small electro-magnet (*see* Fig. 14) made of a piece of soft iron wire, one-eighth of an inch in diameter and three inches long, wound over in opposite ways with two separate insulated wires, the ends of one coil projecting at one end, and the ends of the second coil at the other. This small electro-magnet was balanced beam fashion on pivots, and so arranged that the projecting ends of the wires wound on it could dip in pairs of mercury cups at the two ends of the supporting board, according as the beam was tilted one way or the other. A permanent horse-shoe magnet was fixed so that one end of the beam electro-magnet could play between the poles. The mercury cups on the board were connected together, as shown in the figure. If a battery and coil were connected in series with one pair of mercury cups at one end of the board, it is obvious that matters could be so arranged that the reversals of polarity of the beam magnet as it was caused to tip its connections backwards and forwards into one or other set of cups, could not only maintain the rocking motion, but also interrupt the circuit of the coil. In the following year, 1838, Page had completed new and more perfect induction coils, consisting of two separate circuits, a thick wire primary, and a thin wire secondary, and he describes these coils in a very able Paper, published in June, 1838, in *Silliman's American Journal of Science*, Vol. XXXIV., July, 1838, p. 364.

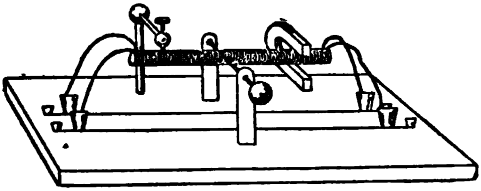
Fig. 14.—Page's Automatic Contact Breaker.

He calls iron cores wound over with two separate circuits "compound electro-magnets," in the use of which phrase he followed Prof. Joseph Henry. These compound electro-magnets, or induction coils, were made with cores, consisting of bundles of fine soft iron wire, or strips of soft hoop iron. The cores were either straight or U-shaped. Dr. Page evidently arrived by independent investigations at a knowledge of the advantage obtained by using such divided iron cores, but whether before or after Bachhoffner it is impossible to say. Page himself states that he used them before February, 1838, when Bachhoffner first used them in England. These compound magnets were, however, induction coils of the form employed by Callan, and by their use Page obtained visible sparks from the secondary circuits, as well as very severe shocks, and produced secondary sparks by the help even of a primary current derived merely from one or two thermo-electric couples. In this same Paper, Page describes a remarkably interesting and ingenious induction coil which he called a "magneto-electric multiplier." He arrived by experiment at the conclusion that when an armature of soft iron was applied to one of his U-shaped compound magnets, the induction, as we now call it, through the secondary circuit for a given current strength in the primary, was much greater than when the armature was not present. Also that the depolarising power of the magnet was much greater when the armature was removed, so as to break the magnetic circuit. Hence it occurred to him that if he could first of all make his iron core a closed magnetic circuit *before* starting the primary current, and then break the primary circuit and open the magnetic circuit by detaching the armature directly afterwards, the combination of these two actions would put in and take out of the secondary circuit many more lines of force in the same time, and hence produce a greater electromotive force in the secondary circuit than if the primary circuit of a straight coil

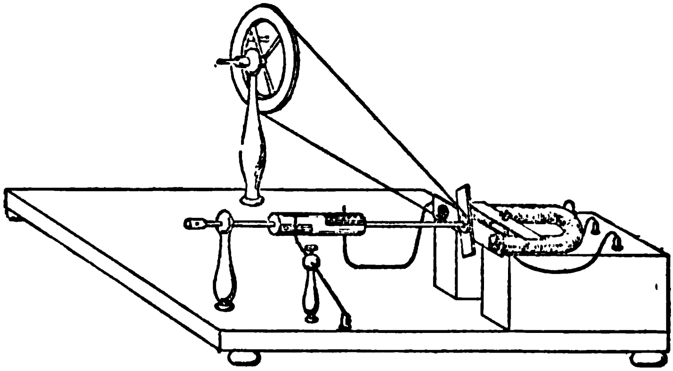

FIG. 15.—Page's "Magneto-Electric Multiplier."

were simply opened and closed. This reasoning shows that at this date Page had acquired a great grasp of the true principles of electro-magnetism. The apparatus with which he put his ideas to the test is shown in Fig. 15. It consisted of a horseshoe shaped induction coil, or a U-shaped compound magnet, the core being made of 500 soft iron wires, 12 inches long, and bent into the shape of a U. The primary coil consisted of five layers of No. 16 copper wire, and the secondary of seven layers of No. 26 copper wire, both being well insulated. This horseshoe magnet was fixed on a wood block, so that its poles projected horizontally, and a soft iron armature fixed to a spindle, so adjusted that it could revolve in front of the poles. This spindle also carried a cylindrical wooden piece, having brass strips on parts of its circumference, and which had contacts made against it by a couple of brass springs. This was the primary current contact-breaker. By shifting the angular position of this cylinder relatively to the armature, it was possible to break the primary circuit at an instant corresponding to any defined position of the soft iron armature. It was normally set so as to break the circuit of the primary current when the soft iron armature was just leaving the position in which it magnetically completed the iron circuit of the magnet. Hence the primary electric circuit and the magnetic circuit were opened, one immediately after the other. The result was a very considerably greater production of electromotive force in the secondary circuit. Page got brilliant sparks from the ends of the secondary circuit of this coil, and unbearably severe shocks. He was also able to get a small arc when carbon points were used as terminals for the secondary, and he found the tension at the ends of the secondary was great enough to enable him to charge a Leyden jar. The same Paper which contains the description of this "electro-magnetic multiplier" also contains some very clear remarks on the use of divided iron cores, and on the magnetism of soft iron. Page employed sometimes cores made of very soft hoop iron, wrapped together, in making his compound magnets or induction coils. He knew very well that soft iron is capable of retaining a considerable amount of magnetism, provided it is not shaken or twisted. He illustrates this by an experiment in which a very soft iron wire was magnetised by being drawn once across the poles of a permanent magnet. It contains a considerable amount of magnetism if handled gently, and will lift up another piece of soft iron wire equal to itself in weight. If, however, it is given a flip with the finger and thumb, it immediately loses nearly all its magnetism. Page also was aware of the depolarising effect which a number of magnetic filaments, such as magnetised soft iron wires, exert on one another when bound into a bundle with similar poles adjacent. On this account, he says, a bundle of fine steel wires will act almost as well as a bundle of fine soft iron wires when used as a core for an induction coil. Page proceeded still more to improve the coil, and in *Silliman's American Journal of Science*, Vol. XXXV., 1839, he communicates another Paper, dated from Washington, Nov. 13, 1838, in which he describes a large induction coil closely resembling modern models. This last coil had a straight core consisting of a bundle of soft iron wires, and the coil wires were wound on a bobbin, having wooden cheeks. The primary wire was a thick copper wire, and the secondary a very fine copper wire. This coil was provided with an automatic hammer break which broke and made a mercury contact (*see* Fig. 16). The hammer head was a ball of soft iron, which was operated by the magnetism of the core. The hammer head was prevented from sticking to the end of the core when attached by the interposition of

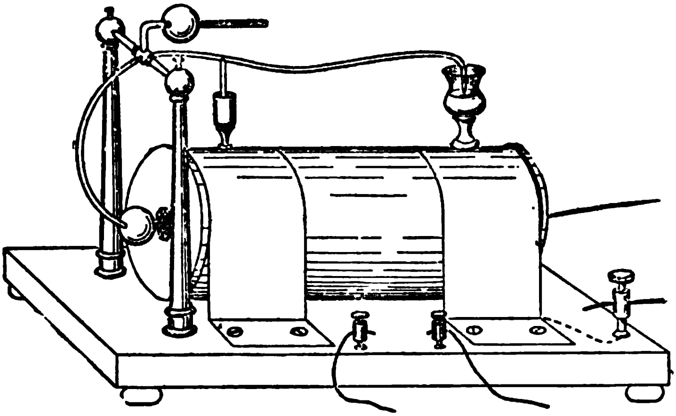

FIG. 16.—Page's Induction Coil (1838).

a small piece of brass. The vibrations of the hammer worked a mercury cup break placed on the coil and which interrupted the primary currents. Page noted the fact that the deflagration of the mercury at the point of break had the effect of prolonging the contact because the primary current continued to flow in the mercurial vapour. Hence, it occurred to him to prevent this by putting oil or alcohol on the top of the mercury to quench the spark and increase the suddenness of the break. This device was revived many years after by other inventors, particularly by Foucault, but it seems first to have been used by Page, in 1838. In this memoir Page made some very excellent remarks upon the action of "closed circuits" in preventing or reducing the inductive action of the primary current upon the secondary circuit. He states that if a closed circuit, such as a metallic sheath or tube, is interposed between the primary or secondary circuits, it more or less annuls the inductive action of the former on the latter. He hence notes that wrapping, what he calls a "compound magnet," *i.e.*, an induction coil with two separate circuits, in a metallic sheath, greatly reduces the

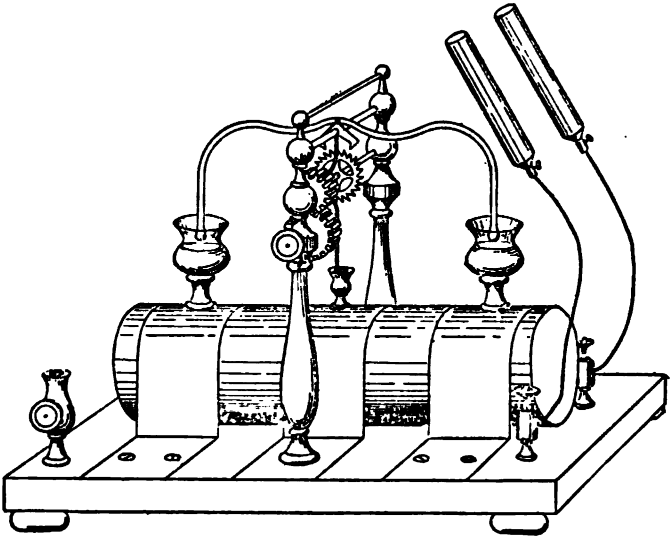

FIG. 16A.—Abbot's Induction Coil (1840).

inductive action of the primary on the secondary, although it does not prevent the action of the primary circuit in permanently magnetising the core. The same action he points out proves prejudicial if bobbins, made of metal, or having metal cheeks, are used upon which to wind the circuits of the coil. Hence, bobbins for induction coils should be made entirely of non-conducting material.

We also find that in 1840, J. H. Abbot, of Boston, U.S.A., constructed a large induction coil (see *Silliman's American Journal of Science*, Vol. XL., April, 1841, p. 107), which was capable of charging a Leyden jar, and which gave small secondary sparks. The break was a hand-worked break (*see* Fig. 16*a*). The secondary terminals were described as being luminous in the dark when the coil was in action. This coil was modelled on Page's.

It is evident from the foregoing that, even in the year 1838, C. G. Page had brought the induction coil to a high degree of perfection by his researches made at Salem and at Washington, and in particular had shown that the secondary circuit could exhibit effects of "tension" and produce electrostatic change in conductors having capacity connected with them when induction coils were used in which the secondary currents consisted of great lengths of fine wire. He had obtained sparks in air from the secondary terminals of coils, and shown the conditions under which these "electrostatic" effects could be exalted. We must also credit him with being an independent inventor of the self-acting hammer electro-magnetic contact breaker.

Continuing his researches, Page made many coils between 1838 and 1850, having highly insulated secondary circuits and vibrating automatic contact breakers. He found, as above observed, that he could charge Leyden jars, diverge the gold leaves of electroscopes, and produce many of the effects hitherto only obtained with electrostatic machines by means of these induction coils. With one of his coils he found he could obtain sparks half an inch long in air from the secondary terminals. He noted, also, the effect of rarefying the air round these terminals on the length of discharge. With one coil, which gave a secondary spark of $\frac{1}{16}$th of an inch in air, he obtained a discharge of about 4½ inches in rarefied air, when the primary circuit was actuated by one single Grove's cell. In 1850 Page constructed a very large coil, of which the primary circuit was a wire or ribbon of copper, one quarter of an inch in diameter. This coil, when worked by 100 Grove's cells, gave sparks from the secondary circuit 8 inches in length.

One striking peculiarity about this large primary coil attracted Dr. Page's notice. When a solid iron core was put into this great helix the primary current took a very sensible fraction of a second to rise to its full value; from $\frac{1}{10}$th to two seconds, according to the position of the iron core. Page also noted a phenomenon, afterwards recorded by Rhyke in 1855, viz., that when the primary circuit was broken just between the poles of a powerful magnet the break-spark was extinguished with a loud explosion, like that of a pistol when fired.*

§ 10. **Wagner and Neef's Automatic Contact Breaker.**—Continental writers generally attribute the invention of the automatic vibrating electro-magnetic contact breaker to J. P. Wagner† and to Neef.‡ These inventors improved upon Page's mercurial break by constructing the vibrating armature with platinum contacts in the form in which it is now used in every trembling electric bell. The apparatus is too well known to need description. A form of Wagner's hammer, as it is generally called, is shown in Fig. 17, intended as an interrupter to the primary circuit of a coil. Du Moncel, however, states that MacGauley, of Dublin, independently invented the form of hammer contact as now used. From this date onwards it has generally been the custom to interrupt the primary circuit of an induction coil, if small, in the manner introduced by Page in 1838, viz., employing the intermittent magnetism of the soft iron core of the coil to work the vibrating hammer of the break, using, however, the platinum contacts of MacGauley or Wagner instead of Page's mercurial cup. On the other hand, when the coil is large, the break is usually made as a separate piece of apparatus with independent magnet, and in that case it is often found best to revert to the mercury cup break of Page, and cover, as he did, the surface of the mercury with oil or alcohol to prevent oxidation, as was done subsequently by Ruhmkorff and others. As is usually the case, useful improvements are invented several times over by inventors who are not familiar with what has already been done. We find in Sturgeon's *Annals of Electricity*, Vol. V., p. 30, a description of a coil by Thomas Wright, of Knutsford, dated 1840, in which he gives a sketch of a neat form of vibrating contact-breaker (*see* Figs. 18 and 19), which is practically the same as that used on all small coils at present. Wright followed Neef and Wagner in suggesting that the contact points should be tipped with platinum. He succeeded in making some "electrotomes," as they were called, in which the spring vibrated so fast as to give out a musical note. Wright also gives details of many coils made by him about this time to determine the best dimensions of the core and of the circuits. It will be seen that by the year 1840 the induction coil had been practically completed in all essential parts, with the exception of the condenser. The separate primary and secondary

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* The greater part of Dr. C. G. Page's valuable work is recorded in his own Papers, published in *Silliman's American Journal of Science* between 1834 and 1850. He published in 1867 a *brochure* entitled the *History of Induction*, which is alluded to by Du Moncel in his work (Vol. II.) *Exposé des Applications de l'Electricité*, but this pamphlet of Page's is not to be found either in the British Museum Library or in the English Patent Office Library.

† See *Pogg. Annalen*, Vol. XLVI., p. 107, 1839; ‡ and *Pogg. Annalen*, Vol. XLVI., p. 104, 1839; and compare *Wiedemann's Galvanismus*, §§ 696 and 737.

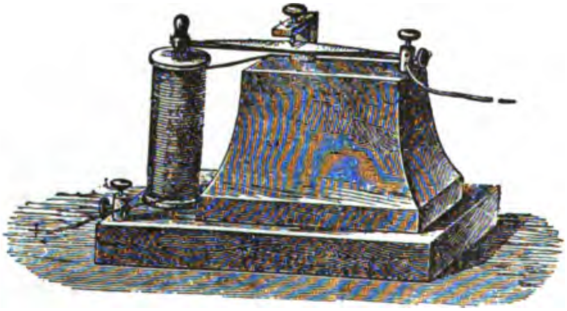

FIG. 17.—Wagner's Automatic Contact Breaker.

circuits of thick and thin wire, the divided iron core and the vibrating contact breaker had been arrrived at and perfected;

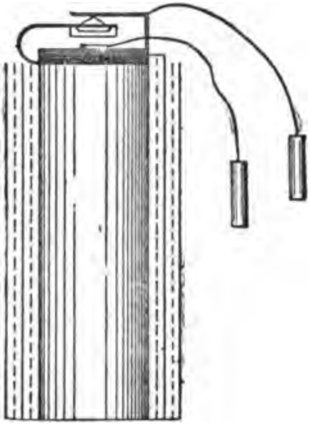

FIG. 18.—Wright's Coil and Contact Breaker.

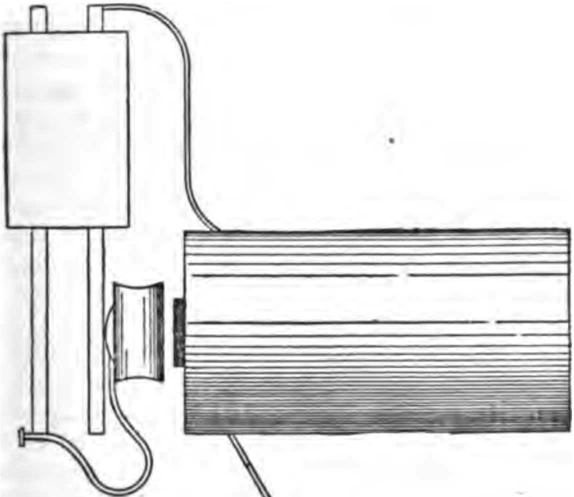

FIG. 19.—Wright's Contact Breaker.

chiefly by the investigations of Callan, C. G. Page, Sturgeon, Bachhoffner, Wagner, and Neef.

§ 11. The Researches of Masson and Breguet.—Between 1838 and 1842 the French physicists, MM. Masson and Breguet, prosecuted researches of a valuable character on the induction of electric currents. In the *Annales de Chimie et de Physique* (3rd Series, Vol. IV., 1842, page 129) will be found a long memoir, summing up the results of their work, which was communicated to the Academy of Sciences on August 23rd, 1841.

This Paper contains an account of very careful experiments on the production of electrostatic effects by secondary induced currents. In their investigations, Masson and Breguet employed a toothed wheel interrupter, or rheotrope, consisting of a brass toothed wheel having the teeth interspaces filled up with wood or ivory; one or more such wheels could be revolved on the same axis, and, by means of springs pressing against the periphery of the wheels, the primary current could be broken, and the secondary circuit closed at instants corresponding to the closing or opening of the primary circuit.

By the help of this apparatus they could separate out the two induced currents, and by means of a condenser and electroscope they examined the electrostatic potential at various points on the secondary circuit. Not being aware of the previous researches of Page, these investigators were apparently under the impression that they were the first to show that a condenser could be charged from the ends of the secondary circuit. Transforming, as they called it, induced currents into static electricity, they produced luminous discharges in vacuo by means of induced currents, and showed that these discharges had all the characters of discharges produced by electrical machines or Leyden jars. These results surprised European physicists, who, as Du Moncel observes, were apparently not aware that similar experiments had already been conducted in America. Amongst the chief results of this investigation was the experimental confirmation of the fact that the two secondary induced currents, the one produced by the commencement of the primary current, and the other produced by its cessation, consisted of equal quantities of electricity set flowing in opposite directions. Also the other important fact that the maximum value of the electromotive force of the secondary current at break of the primary is much greater than the maximum value of the secondary current at the starting of the primary, was stated by them. Hence it became clear that the direct or break-induced secondary current could traverse air spaces or overcome resistance which was impossible in the case of the inverse or make-induced current. The researches of Masson and Breguet established on a quantitative basis more firmly than before the facts of the induction of electric currents, but they did not achieve more than had previously been done in exalting the spark-producing power of secondary coils.

§ **12. Henley's Coil.**—In the years between 1842 and 1851 very little progress appears to have been made in improving induction coils. Some modifications of arrangement either of the coil or the contact breaker were introduced. To this period, probably, belong two such varieties which are mentioned and described by Noad (*Manual of Electricity*, Vol. II.). One of these is represented in Fig. 20. The primary coil consisted of about 35ft. of insulated copper wire (No. 21), and the secondary of 1,400ft. of silk-covered copper wire (No. 20). The battery contact is renewed and broken by the rotation of the soft iron bar, which, mounted between two brass supports, is situated immediately over the axis of the coil, in which is

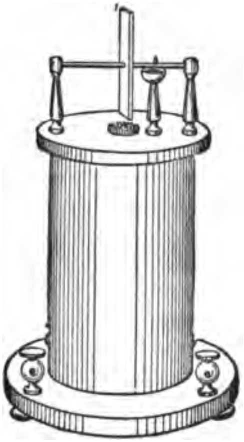

FIG. 20.

placed a bundle of iron wires. The current from the battery passes through the support and the axis carrying the iron bar; and the contact is interrupted by the small steel point, dipping as the bar revolves into and out of the mercury contained in the brass cup mounted on the brass pillar, through which the circuit is complete. This apparatus formed a self-acting shocking coil, but could produce no sparks from the secondary. Noad describes also an interesting form of coil which bears some relation to Page's electro-magnetic multiplier, and which, Noad says, was given to him by Mr. W. T. Henley. It is represented in Fig. 21. A series of U-shaped bars of soft iron bolted down to a base board was wound with four coils of No. 14 covered copper wire, to within an inch of either extremity. Over this was wound 1,000 yards of No. 34 silk-covered wire in one continuous length. A revolving iron armature rotates on a vertical spindle, so that in passing over the

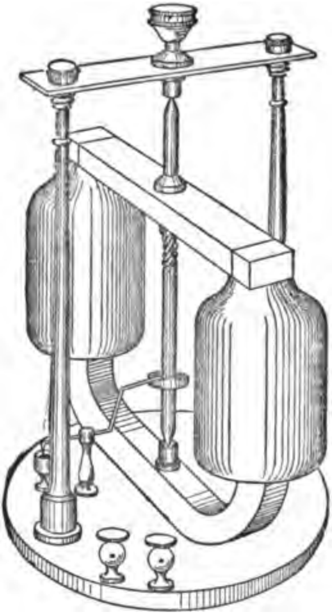

FIG. 21.—Henley's Induction Coil.

magnetic poles it nearly completes the magnetic circuit. The contact breaker consists of a bent lever, one end of which dips in a mercury cup and is so pivoted that the motion of the other end against the undulating surface of a cam-wheel attached to the spindle serves to dip the first-named end in and out of the mercury. The break of the primary circuit is so adjusted as to take place just after the soft iron armature has completed the magnetic circuit. Actuated with a battery of 10 cells this coil gave sparks one-eighth of an inch long in air, and remarkable for their quantity. It is easily seen that the appliance is, at the same time, an induction coil and also an electro-magnetic motor, and that a suitable arrangement of the time of making and breaking the primary circuit will cause the soft iron armature to be kept continuously in motion. It was noted as a curious fact that when the ends of the secondary circuit were metallically joined the spark at the primary break was much reduced. This is obviously due to the fact that the closing of the secondary circuit reduces the self-induction of the primary coil. These pieces of apparatus formed no real advance on what had been done before.

§ 13. **Ruhmkorff's Induction Coils.**—In 1851, M. Ruhmkorff, a skilful mechanician in Paris, profiting by the experiments of Masson and Breguet, and probably not aware of the researches of Callan and Page, addressed himself to the problem of increasing the spark-producing power of the induction coil, with the object of exalting the electrostatic effects which Masson and Breguet had produced. He paid the greatest attention to the insulation of the secondary coil, insulating the covered wire by passing it through melted shellac, and separating each layer of wire from the next by means of varnished silk or shellaced paper. He greatly lengthened the secondary circuit, employing in some coils five or six miles of secondary wire, and he insulated with care the primary from the secondary circuit by employing a glass tube on which to wind the secondary circuit, and glass cheeks to preserve the wire in place at the ends. He also supported the ends of the secondary wire on glass pillars. He provided, also, a simple form of current-reverser to change the direction of the primary circuit, and greatly improved the action of the vibrating hammer interrupter. The greatest service was, however, rendered by Fizeau by his application of the condenser (*Comptes Rendus*, 1853, Vol. XXXVI., p. 418), and Ruhmkorff carefully studied the appropriate dimensions of the condenser. This condenser he made at first of a sheet of oiled silk, covered on both sides with tinfoil; later he employed sheets of well-selected paper, carefully varnished, and coated with tinfoil on each side. This condenser was placed in the base of the induction coil, and the two terminals of the condenser connected to the two opposite sides of the "break" points. The condenser was made by varnishing close-grained but thin paper with shellac varnish. Each sheet was then examined for defects. A number of sheets of tinfoil were cut, each somewhat less in size than the sheets of varnished paper. A pile was made by building up alternate sheets of paper and tinfoil, placing each alternate sheet of tinfoil so as to protrude from the paper pile on opposite sides. The pile was then compressed, and all the tinfoil sheets on one side connected together, and also those on the other. Hence the arrangement formed a compact kind of Leyden jar, of which one set of tinfoil sheets formed the "outside" and the other set the inside surfaces, the varnished paper being the dielectric.* In the larger sized coils Ruhmkorff found it convenient to revert to the mercury-break of Page, and this was modified and re-invented by Foucault, who again suggested the advantages of making a break by withdrawing a steel or platinum point from a mercury surface, covered with alcohol or oil. Aided thus by Fizeau and Foucault, Ruhmkorff produced induction coils which enabled him to obtain secondary sparks several centimetres in length. It was, however, found that the tendency to internal sparking, and to rupture of the insulation of the secondary circuit, became very great when the coils were enlarged beyond a moderate size. In his later coils, after 1855, Ruhmkorff adopted a mode of construction which was suggested by Poggendorff, Stöhrer, and l'Abbé de la Borde, about 1854, viz., to wind the coil in sections so that no two portions of the wire which are closely adjacent are at very different potentials. When a coil is built up by winding layer over layer in the ordinary manner, the ends of the layers of wire, and particularly the similar ends of the first and last layers, are at very different potentials, and there is a great tendency for the discharge to pass between these points. In fact the sparking distance of the coil is limited by the distance of these portions of the wire. Under these conditions internal sparks were found to pass and to break down the insulation of the secondary circuit. The suggestion to wind the wire in separate partitions originally came from the English electricians, Edward and Charles Bright, who, in a patent taken out in 1852,* describe a method of thus winding electro-magnets, and in their fourteenth clause say, "The manner in which our fourteenth improvement may be carried into effect is as follows: —It is well known that the ordinary mode of winding the wire on coils is to wind it backwards and forwards upon the core. Our improved plan is to divide the core lengthways into compartments, by means of separating pieces fastened to the body of the coil, before winding and dividing the coil into compartments. In winding the wire, one end compartment is filled, and then the next, and so on." In adopting this method of winding, the flat coils of wire can be wound independently, and are then so joined up that the outside end of the wire on one coil is joined to the outside end of the wire of the next compartment, and yet the winding follows the same direction in each bobbin or separate flat coil. Hence no two portions of the wire at very different potentials are very close to each other, or, if they are, they are well insulated.

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* The theory of the action of the condenser has been discussed in Vol. I. *Alternate Current Transformer*, § 7, Chap. V. When the contact breaker is provided with a condenser whose opposite surfaces are connected to the two sides of the break points, there are two distinct kinds of sparks observable at the break. There is first the spark at "break," due to the self-induction of the primary circuit, and there is the spark at "make," due to the discharge of the condenser. Rijke made the observation that the condenser is more effective in lengthening the secondary spark of the coil when the break points, or points of contact, are of gold, copper, or silver, than if they are of platinum. The discharge spark of the condenser, when a too small condenser is employed, is very bright and hot, and sometimes welds together the platinum contact points. The remedy for this accident when it occurs is to employ a condenser of larger capacity. Callan (*Phil. Mag.* [4] Vol. XIV., p. 337, 1857) suggested the employment of amalgamated copper contacts for the break, working in or smeared with oil to prevent oxidation and increase the suddenness of the break.

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* British Specification, No. 14,331, of 1852.

One of Ruhmkorff's largest coils made about 1867 was 52 centimetres in length, and the secondary circuit was divided into 80 flat coils or partitions, each compartment being occupied with five or six spirals—that is, being of a width equal to five or six times the diameter of the covered wire. The secondary circuit consisted of copper wire one-tenth of a millimetre in diameter, and 100,000 metres, or 62 miles, in length. The different compartments of the secondary circuit were insulated from one another with shellaced paper or varnished silk, and the different layers of wire in each compartment also insulated with shellac. The secondary circuit was wound upon a tube of glass as a support. The condenser employed with this coil was formed of 100 sheets of tin of a length of 50 centimetres and a breadth of 25 centimetres, insulated with paper covered with shellac, and formed a condenser having a total surface of about 12 square metres. The primary wire in this coil had a thickness of about three millimetres. This coil could give sparks 40 centimetres in

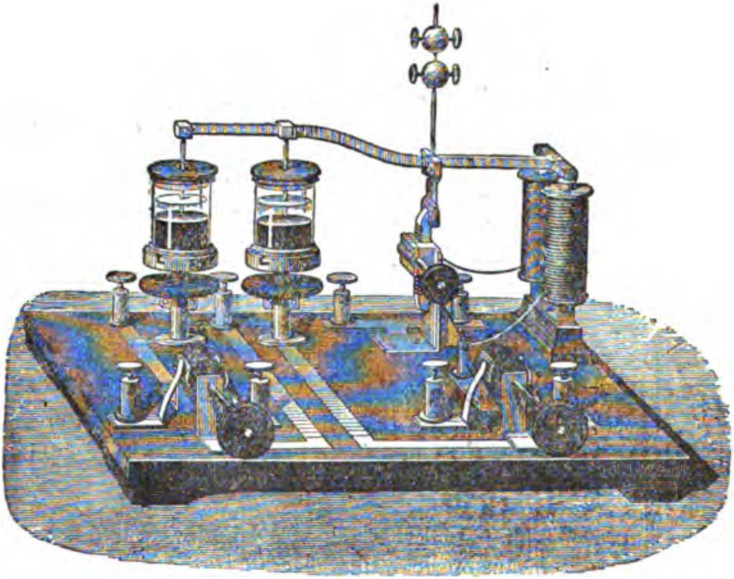

FIG. 22.—Ruhmkorff's Mercurial Break.

length between the ends of the secondary circuit. The coil was usually worked by the current from six large Bunsen cells. For such large coils Ruhmkorff and Foucault found the hammer-break with platinum contacts quite unsuitable, since the contact points are rapidly burnt away by the spark at "break," due to the self-induction of the primary circuit, and by the additional spark at "make" of the contact, due to the discharge of the condenser. Hence they revived and improved the mercury break, covering the surface of the mercury with alcohol, and breaking the primary circuit (*see* Fig. 22) by a platinum point automatically lifted out of the mercury.*

§ 13a. Improvements on Ruhmkorff's Coils.—Ruhmkorff succeeded in producing induction coils capable of giving very long sparks from the secondary circuit, but the insulation of these coils was not always found to be permanent. Du Moncel tells us that Fizeau, in endeavouring to join up several Ruhmkorff coils with the secondary circuits in series, felt severely the need for better insulation, and that M. Jean, a simple amateur mechanician in Paris, solved the problem, in 1854, by plunging the whole coil beneath the surface of a liquid insulator, viz., oil of turpentine; and by constructing coils in this manner, insulated with a fluid insulation, Jean succeeded in getting sparks of 30 centimetres in length at a time when no one, at least in France, had approached this length.† Du Moncel says that these experiments of Jean were neglected or lost sight of, and that Ruhmkorff finally succeeded in obtaining sparks of 60 centimetres in length by building up the coil in sections.

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* Foucault, *Comptes Rendus*, Vol. XLIII., p. 44, 1856.

† Jean's experiments are recorded in the *Comptes Rendus*, Vol. XLVI., p. 186, 1858. It is curious to observe that Du Moncel naturally claims priority for his countryman Jean with respect to this suggestion, to immerse the whole induction coil in oil or insulating fluid to obtain higher insulation, whilst Wiedemann (see *Galvanismus*, § 911) claims for Poggendorff the origination of the idea. Modern inventors have again become alive to the value of this suggestion, and patents have been taken out for immersing alternate current transformers in oil as a means of increasing the insulation. Mr. Brooks of late years has especially drawn attention to the use of certain oils as insulators and to the practical employment of them in cables for high pressure currents.

Jean's coils were built up as follows: The primary wire consisted of four layers of wire and the secondary circuit of 50 layers. The primary wire had a thickness of 1½ millimetres and the secondary ·25 millimetre. The different layers of the primary and secondary were separated from each other by well-dried blotting paper. The whole coil was placed in a glass vase and filled up with oil of turpentine. The ends of the secondary wire where they emerged from the liquid were passed through glass tubes. The whole coil was baked and dried to eradicate moisture previous to immersion in the insulating liquid. M. Jean even performed this desiccation in a vacuum, and, by taking the greatest pains to avoid contact of air after and during this drying process previous to placing it in the liquid, he obtained very extraordinary insulation. There can be little question that M. Jean was here on the right track, and that this liquid insulation had many important advantages.

§ 14. Poggendorff's Researches on Induction Apparatus.—In the *Philosophical Magazine* for July, 1855, is to be found a long Paper by Poggendorff, giving an account of his researches and suggestions with regard to the induction apparatus of Ruhmkorff. He begins by criticising the construction adopted by Ruhmkorff, as illustrated by one of his coils in the physical laboratory of the University of Berlin, and points out in the first place the defect we have already referred to in the original manner of winding the coil, and the advantages to be derived from winding the secondary coil in sections. With respect to the insulation of the wire, he advises, instead of shellac dissolved in alcohol, the use of an easily fusible insulator, such as spermaceti, or a mixture of wax and oil, or paraffin wax, or, better still, the use of a *fluid* insulator, such as vegetable oil, or oil of turpentine, so that permanent defects of insulation could not occur. He also proposed insulating the silk-covered wire by first boiling it in spermaceti to get rid of moisture and air. Poggendorff experimentally examined the construction of each element of the coil, with the object of ascertaining the best arrangement and proportions of each part. With respect to the condenser, he adopted a suggestion which apparently emanated from Halske—viz., to use mica for the dielectric, and he convinced himself of the great superiority of mica over oiled silk in this portion of the apparatus. Owing to the expense of procuring large sheets of mica, he also used very thin paper, varnished with amber varnish, as a substitute. Also he used thin gutta-percha sheet for the same purpose. Poggendorff made many experiments with the object of ascertaining the exact influence of the dimensions of the condenser upon the spark-producing power of given coils. He came to the conclusion that the stronger the primary current and the longer the primary circuit, the greater must be the capacity of the condenser in order to obtain the maximum possible secondary spark. Poggendorff established the following facts, some of which had previously been arrived at by Masson and Breguet:—

(i.) When the terminals of the secondary circuit are joined by a metallic wire, or other good conductor, induced currents at "break" and "make" of the primary circuit, which are in opposite directions, circulate in the secondary. These currents are equal in quantity, but different in electromotive force.

(ii.) If a good conducting electrolyte, such as dilute sulphuric acid, is introduced into the secondary circuit, oxygen and hydrogen are liberated at both poles of the voltameter.

(iii.) If the circuit of the secondary coil is interrupted by a thin stratum of air or gas so that the secondary circuit is not complete, then only one of the secondary currents passes, viz., that produced at the break of the primary circuit. Hence we have, then, phenomena of tension at the ends of the secondary circuit. If an electroscope is touched for a moment against one of the terminals of the secondary it will become charged, but the sign of that charge will be a matter of chance, depending on the instant when it was so touched. If, however, a spark is passed across an air-gap into the electroscope from either terminal of the secondary it will always give one kind of charge, viz., that due to the state of the secondary pole when the primary current is interrupted. The action of the condenser in strengthening the secondary current produced at the "break" of the primary is only seen when the circuit of the secondary circuit is interrupted by an air-gap or circuit of high resistance. When the secondary circuit is completed by a better conducting medium, such as a partially exhausted tube, the action of the condenser is much less apparent. Poggendorff also examined the phenomena presented when the currents from the secondary coil are employed to charge a Leyden jar. He noted the effects, independently observed by Sir W. Grove, and published by him in the *Philosophical Magazine* for January, 1855, which attend the secondary discharges when a discharging path is opened across the terminals of the condenser thus applied. Poggendorff states that, in December, 1854, he communicated to the Berlin Academy the observation that if a Leyden jar has its internal and external coatings connected respectively to the two terminals of the secondary coil, and if wires are also brought from the terminals of the secondary coil to within a short distance of each other, snapping, bright intermittent sparks will be obtained, quite different in appearance from the thin, bluish continuous sparks of the ordinary secondary discharge. *Cœteris paribus*, these discharge sparks are, according to Poggendorff, stronger the more powerful the battery, and the smaller the charged surfaces.

Grove discovered, quite independently of Poggendorff,* the effect produced by a Leyden jar connected across the secondary terminals, but he examined at much greater length the whole phenomenon. Briefly, he found it to be as follows:—If a Leyden jar has its outside coating connected to the inner end of the secondary circuit of an induction coil, and its inner coating to the outer end of that circuit, and if a pair of discharging points are connected across between the two coatings of the jar, then when the coil is set in action and the discharge points adjusted to a proper distance, loud, brilliant intermittent sparks jump across. These sparks are much more brilliant and solid than the ordinary discharge of the secondary circuit, and take place at a slightly less distance. If, now, the battery power or number of cells operating the coil is increased the effect is only to increase the sparks at the primary contact breaker, but not much to increase the secondary discharges. When, however, a larger Leyden jar, or another Leyden jar joined in parallel with the first, is taken and connected to the secondary the effect is immediately to decrease the primary spark and to increase the secondary spark. Hence Grove found that he could apparently go on adding cells to the battery producing this primary current, or increase the primary electromotive force and Leyden jars to the secondary circuit, or increase the capacity of the secondary circuit, over wide limits, and with each such addition the brilliancy and length of the discharges from the secondary terminal were increased. In seeking for an explanation of this effect we have to bear in mind that the Leyden jar or condenser which is joined across the secondary terminals acts as a conductor of electricity *during* the time in which the induced electromotive force in the secondary circuit is increasing in amount. Also, the capacity of the condenser reacts with the self-induction of the secondary circuit to increase the maximum potential difference at the terminals of the secondary coil in a manner to be discussed more fully later on. During the period of time in which the secondary inverse induced current is flowing into the condenser it is being charged. At the instant when the secondary induced electromotive force becomes zero the condenser begins to discharge. Owing, however, to the great self-induction of the secondary circuit of the coil the charge of this condenser does not flow back through the secondary coil, but springs across the parallel air-gap, making a spark. The greater brilliancy and noise of this spark, as compared with the ordinary discharge of the secondary circuit, is due to the greater quantity of electricity which passes at each discharge. Poggendorff made some very instructive experiments with two or more induction coils,* which if they had been carefully studied by subsequent inventors might have done much to prevent misconception and error. Poggendorff took two similar induction coils, which we will call A and B, and arranged them with their primary coils *in series.* A was allowed to give sparks from its secondary circuit whilst the secondary circuit of B remained open and having its soft iron core removed. The introduction of the soft iron core into the primary coil of B at once weakened the sparks from the secondary circuit of A. Hence, says Poggendorff, it follows that "two complete instruments combined one after the other mutually disturb one another, and the total effect is not equal to the sum of the effects which each would produce with the same intensity of galvanic current."

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* See *Phil. Mag.*, Vol. IX., Series 4, 1885, p. 1.

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* See *Phil. Mag.*, Vol. X., 4th series, 1855, p. 137.

He then modified the experiment by placing the coils A and B *alongside* of one another, so that the primary circuits were joined in parallel, and he found that the insertion of the soft iron core into B *increased* the sparks given by A. He found that in the first case, when the primaries were in series, the closing of the secondary circuit of B again reproduced the sparks at their former intensity at the secondary circuit of A; whilst, in the second case, when the primary circuits of the coils were in parallel, the subsequent closing of the secondary circuit of B destroyed the augmentation of the sparks at the secondary circuit of A. The explanation of these effects is obvious in the light of what is now known as to the effect of the closed secondary circuit upon the impedance of the primary circuit. When the primary coils were in series, the introduction of the iron core into B increased the impedance of the whole circuit, and hence decreased the primary current and the secondary sparks of A, but the subsequent closing of the secondary circuit of B partly annulled the impedance of the primary circuit, and hence reaugmented the secondary sparks of A. Similar explanations apply to the case of the coils with primaries in parallel. If these experiments had been carefully considered by subsequent inventors it would have been seen that induction coils with their primaries in series are not independent of each other, and that the strength of the primary current is affected by the opening or closing of the secondary circuit of any one of them. Poggendorff examined very carefully the action of the contact breaker, both when operating in air, as well as when immersed in various liquids, and also when in a good vacuum. He found that, when the contact points of the contact breaker were immersed in pure distilled water or alcohol, the length of the secondary spark was augmented, when compared with its length, when the contact breaker operated in air. He made also the curious observation that when the contact breaker on the primary circuit operated in a good vacuum its action in lengthening the secondary spark was so much increased that it produced very nearly the same effects when acting without a condenser as did a contact breaker provided with a condenser when acting in air.

§ 15. Foucault's Experiments with Two Coils.—In the *Comtes Rendus* for 1856 (Vol. XLII., p. 215), Foucault describes an interesting experiment which he made with two Ruhmkorff induction coils. He desired to obtain long sparks by adding together the potential of two induction coils. With this object he joined the primary circuits of two similar coils in parallel, and operated them by the current from one and the same battery. Under these circumstances the contact breakers did not vibrate in step, and the secondary spark length, resulting from joining the two secondary circuits in series in the proper way, was not the sum of the lengths of the separate secondary sparks. He discovered an ingenious way of making the contact breakers keep in step. This was effected by joining a piece of wire across from the end of one primary coil to the similar end of the other, this junction being effected between the contact breaker and the beginning of the primary coil. When this was done each hammer kept the other in step with itself, and, on joining up the secondary circuits in series in the proper manner, he obtained a secondary spark double in length (viz., 18 or 20 mm.) of that of each coil separately.

§ 16. Stöhrer's Induction Coil.—In 1854 Emil Stöhrer directed his attention to the improvement of the induction coil,* and produced a form of coil which is represented in Fig. 23. The instrument consisted of a primary wire and core of divided soft iron arranged in a vertical position, the iron wires being of 1mm. diameter, and standing loosely in a cylinder of wood so that they could be removed one by one if desired. The iron wires were varnished with shellac. The primary coil consisted of six layers of double covered wire 1mm. in diameter, the height of the whole spiral being 20 centimetres, and its diameter over all 50mm. The secondary coil consisted of three independent coils wound on separate bobbins made of varnished paper with cheeks of pear-tree wood. The wire was insulated with silk and well varnished, and insulated with a mixture of wax and resin. Stöhrer employed an independent electro-magnetic contact breaker, and a condenser of which the dielectric consisted of waxed cloth. He obtained good secondary sparks 12 or 14 "lines" in length. He tried producing, as Sinsteden had suggested, an arc light between coke points by means of the secondary discharges, but he was not aware of the previous results of Callan or of Page in this respect, and his coil evidently furnished too small a "quantity" of current to enable him to obtain an arc.

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* See *Poggendorff's Annalen*, May, 1856; also *Phil. Mag.*, 1857, Vol. XIII., 4th series, p. 55.

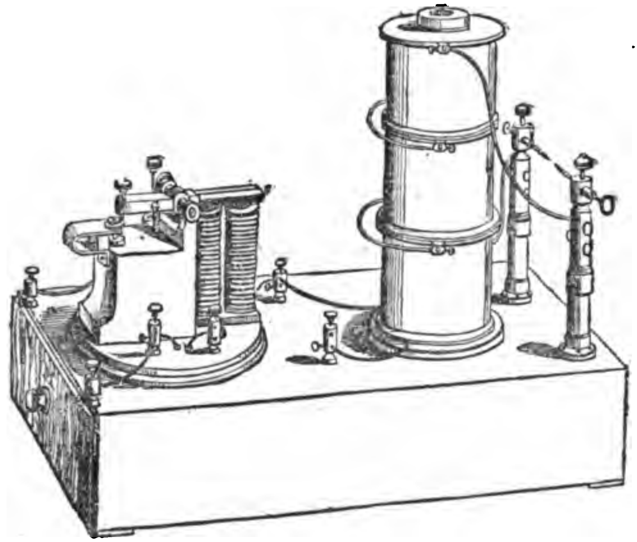

FIG. 23.—Stöhrer's Induction Coil (1856).

§ 17. **J. N. Hearder's Induction Coils.**—Mr. J. N. Hearder, of Plymouth, began, in December, 1855, the construction of induction coils, and his Papers describing his work are to be found in the *Philosophical Magazine* for November and December, 1856 (4th series, Vol. XII., p. 377).* Hearder had his attention drawn to the subject by the Paper of Grove in 1855, to which reference has been made already, on the employment of a Leyden jar in connection with the secondary circuit, and this Paper stimulated him to examine the construction of Ruhmkorff's induction coil. After many experiments he was successful in producing a coil for which he obtained a silver medal from the Royal Cornwall Polytechnic. It appears that up to the time of Hearder's experiments he (Hearder) had not, apparently, seen any one of Ruhmkorff's induction coils capable of giving a greater length of secondary spark than three-quarters of an inch. Hearder adopted sheet gutta-percha as his insulating material for the secondary coil, and he describes the chief differences between his own and Ruhmkorff's coil as follows:—He says (*Phil. Mag.*, Vol. XIV., 4th series, 1857) that Ruhmkorff's secondary wire was insulated with cotton, whilst he used silk-covered wire. Ruhmkorff employed shellaced paper between the layers of the secondary coil, whilst he used sheet gutta-percha or thin vulcanised sheet india-rubber. He also claims that he improved the iron core by using smaller iron wires than Ruhmkorff, and that, in place of oiled silk for the condenser dielectric, he substituted vulcanised india-rubber, gutta-percha, or varnished cartridge paper. He also states that he improved the contact breaker by using a stiffer spring, the rate of vibration of which he could alter, within certain limits, at pleasure, by means of a screw.

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* It is stated in Noad's *Manual of Electricity*, Part II., that Hearder began his work on induction coils in 1846, but this is incorrect.

Hearder noted particularly the limitation imposed by the tendency to discharge from layer to layer of the secondary coil over the ends of the layers of insulator, and he prevented this by extending the sheet gutta-percha placed between the several layers of wire a good way beyond the wire windings, so that the discharge would have to take a longer path through air to get round. A considerable controversy sprang up between Mr. J. N. Hearder and another improver of the induction coil, Mr. C. A. Bentley, as to who was the first to suggest these modifications, and was continued with some bitterness between them (see *Phil. Mag.*, Vol. XIII., 1856, p. 325). Bentley's description of his coil is to be found in the *Philosophical Magazine* for 1856 (Vol. XII., 4th series, p. 319). He constructed a coil capable of giving secondary sparks two inches long in air when the primary current was produced by four or five Grove's cells. Bentley also adopted sheet gutta-percha for the insulation of the various layers of the secondary coil, but whether before or after Hearder it is difficult to say. He employed an electro-magnetic break having a very stiff spring to the hammer, the time of vibration of which he could vary at pleasure. He used also a condenser made of tinfoil and varnished paper.

Hearder constructed about this time a coil some 12 inches in length, in which the secondary circuit had a length of three miles, and from which he obtained secondary sparks about three inches in length. He noted that if the discharge was taken between fine platinum terminals not more than 0·5 inch apart, the negative terminal became white hot very soon, and began to melt. He made many experiments on discharges in air and in vacuo between terminals of different forms.*

Hearder published a Paper in the *Philosophical Magazine* for 1857 (Vol. XIII., p. 325), in which he makes many observations on the heating power of the secondary discharge, both when the terminals were connected to a Leyden jar in the manner described by Grove, and when they were not. He found that whereas the simple secondary current could not, under certain circumstances, heat a few inches of platinum wire red hot, the mere interposition of a Leyden jar across the secondary terminals caused the platinum wire to be heated to redness, or to be fused, thus showing an increase in the quantity of each discharge.

Bentley asserted that he had independently adopted these same improvements as Hearder, and that, by following this mode of construction, Mr. Ladd had obtained sparks 4½ inches long. The points at issue between these inventors are not very important except as showing that several minds had addressed themselves to improving Ruhmkorff's coil, and that the causes limiting the sparking distance were gradually being generally understood.

§ 18. **Ritchie's Induction Coils.**—Mr. E. S. Ritchie, of Boston, U.S.A., began apparently to study the construction of the induction coil in or about 1857, and, probably, not knowing what had been done by Poggendorff, he again brought forward the suggestion of insulating the secondary coil vertically instead of horizontally. A Paper by Ritchie is to be found in *Silliman's American Journal of Science* for November,

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* See *Phil. Mag.*, Vol. XII., 4th series, 1856, pp. 377 and 443.

1857 (Vol. XXIV., p. 45). In this Paper, Ritchie enumerates the causes of the difficulties met with by Stöhrer and Hearder in lengthening the secondary spark beyond three inches, and proceeds to describe his own improvements. Ritchie wound the secondary wire on a glass tube, beginning near one end and winding the wire in a sort of very steep cone (*see* Fig. 24). When this cone of wire was wound on, a *washer* or disc of vulcanised rubber was slipped on and cemented with beeswax and resin, and the end of the wire passed down and insulated with a strip of rubber, and then another cone of wire built up until the whole tube was wound full of coils, insulated from each other with washers or discs of sheet rubber. With a helix so made of 7,000ft. of wire Ritchie obtained a secondary spark of 2½ inches, and with 30,000ft. of wire a spark of six inches. He supplied the above coils with condensers, having respectively 30 and 75ft. of coated surface, the insulator being thin sheet gutta-percha. He found that it was very important to get high insulation between the primary and the secondary coils, and that it was necessary to overlay the glass tube on which the secondary was wound with many sheets of gutta-percha tissue. In 1859 Ritchie sent to France, by McCulloch, a coil made in the above way, which gave secondary sparks 35 centimetres in length, which astonished the French savants, they, as Du Moncel says, not knowing nor caring to know the results of the previous work of M. Jean. A recent coil, made about 1860 by Ritchie, is figured by Du Moncel in his book on the Induction Apparatus of Ruhmkorff, and is shown in Fig. 25. The coil was 120 centimetres in length, and contained 52 kilograms of wire, and weighed in all 112 kilo-

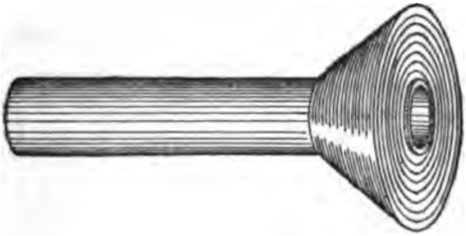

FIG. 24.

grams. The bobbin was composed of two separable portions, and, in fact, was two distinct coils. The core was a bundle of iron wires each one millimetre in diameter. The primary coil was 60 metres long, and constructed of wire five millimetres in diameter. The secondary coil was 71,200 metres, or nearly 45 miles in length, and constructed of wire ·18 millimetre in diameter. It was made of the purest copper, covered with silk, and wound in a series of flat helices of one thickness of wire, the different spirals being insulated with paraffined paper. The insulation between the primary and secondary coils was separated by a glass tube, and layers of vulcanised caoutchouc placed over it. The condenser consisted of sheets of tinfoil of 30 square decimetres in area, insulated with oiled silk, and arranged so that more or less of the surface could be utilised. The interruptor was a hammer-break, actuated by an electro-magnet separate from the coil. The length of each section of the bobbin was 33 centimetres, and the external diameter of the coil 22·8 centimetres. With the currents from three large bichromate cells the secondary sparks were 53 centimetres in length.

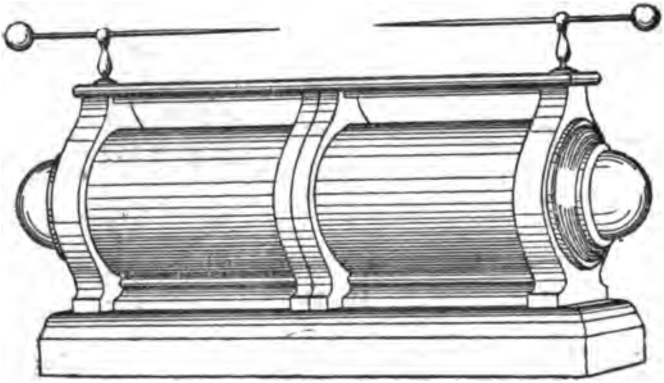

FIG. 25.—Ritchie's Induction Coil (1859).

§ 19. **Mr. Gassiott's Large Induction Coil.**—In 1858, Ritchie constructed, to the order of Mr. John P. Gassiott, a large induction coil, which is thus described by Mr. Gassiott in the *Philosophical Magazine* for 1858 (Vol. XV., 4th series, p. 466):

"The primary coil is of wire of No. 9 gauge, the helix in three layers and 15in. in length, taking altogether 150ft. of wire. The iron core is 18in. in length and about 1¾in. in diameter, of annealed iron wires, No. 16 gauge, annealed with the very greatest care, having been a fortnight in cooling. The primary wire has a cover of gutta-percha, one-tenth of an inch in thickness; over this a glass tube. The secondary helix is divided into three bundles, each five inches in length, wound on cylinders of gutta-percha, the total length of secondary wire being 73,650ft., or 14 miles." The secondary wire was insulated and wound vertically, that is, in separate flat helices. The condenser consisted of varnished tissue paper, three layers of each sheet between every sheet of tinfoil, and there were three condensers which could be employed, of 50, 100, and 150 square feet of coated surface respectively. The coil would give 12¼in. sparks. The interruptor was a ratchet break worked by hand, which enabled various rates of interruption to be applied. This coil was used by Mr. Gassiott in his researches on electrical discharge in vacuo, and gave very fine effects.

§ 20. **Sir. W Grove's Employment of Alternating Currents with an Induction Coil.**—Shortly after the publication of the description of Wilde's magneto-electric generator, Sir W. Grove had the idea of exciting an induction coil with an alternating current. He accordingly applied an ordinary medical magneto-electric machine to the primary of a Ruhmkorff coil, first screwing up the contact breaker of the coil, so as to close the primary circuit, and cut out the condenser. He found to his surprise that he could get no secondary discharge at all. When, however, he opened the contact breaker, so as to place the condenser in series with the primary coil and the magneto-electric machine armature, he got sparks of about one-third of an inch in length between the ends of the secondary coil. Not being able himself to see fully the reason for this he appears to have shown or described the experiment to Clerk-Maxwell, who sent him the explanation of it. (See *Phil. Mag.*, Vol. XXXV., 5th series, 1868, p. 360.)

Maxwell pointed out that the reason why he obtained no sparks from the secondary circuit, when the condenser was short-circuited, and the magneto-electric machine was applied directly to the primary of the coil, was because the self-induction of the primary coil prevented the alternating electromotive force of the generator from developing any but a very small current in the primary coil. When, however, the condenser was thrown into series with the primary coil by opening wide the contact points, the capacity of the condenser annulled a great part of this self-induction of the primary circuit, and hence permitted the alternating E.M.F. of the generator to send a much larger current through the primary coil, and this was able to generate a very considerable secondary current and secondary electromotive force. The condenser neutralised in part the impedance of the primary circuit. In this same Paper, Clerk-Maxwell sketched out the mathematical theory of the shunted condenser in series with an inductive circuit as follows:—Let V_0 be the maximum value of the periodic electromotive force of the generator, and let R and L be the resistance and inductance of the primary circuit of the coil, and C the capacity of the condenser shunted by a non-inductive resistance, r, arranged as in Fig. 26. Then the following relations hold good:—Let v_1 be the potential difference of the condenser-plates at any instant, and let i_1 be the current through the primary coil, and i_2 the current through the condenser shunt. Also let I_1 be the maximum value of the current in the primary coil. If v_0 is the E.M.F. of the generator, then we may write

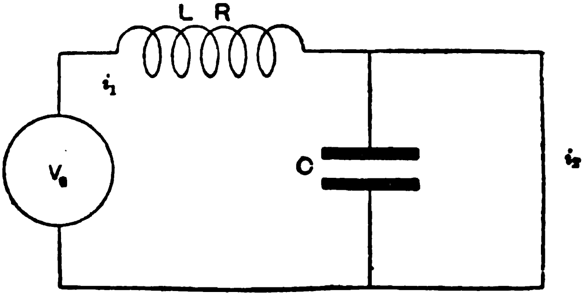

FIG. 26.

$$v_0 = V_0 \cos p t$$

as the expression for this instantaneous value of the E.M.F. in terms of its maximum value, where p stands for 2π times the frequency of the alternating current or electromotive force; also we can write

$$i_1 = I_1 \cos (p\,t + a),$$

and
$$v_1 = r\,i_2.$$

Hence we have
$$C\frac{d\,v_1}{d\,t} = i_1 - i_2,$$

and
$$V_0 \cos p\,t + R\,i_1 + L\frac{d\,i_1}{d\,t} + v_1 = 0,$$

as equations true at any instant, and it is easy to deduce that the maximum value I_1 of the current in the primary is given by

$$I_1^2 = \frac{V_0^2\,(1 + C^2 r^2 p^2)}{r^2\{(1 - L\,C\,p^2)^2 + C^2 R^2 p^2\} + 2\,R\,r + R^2 + L^2 p^2}.$$

If $r = 0$, that is, if the condenser is short-circuited, this reduces to

$$I_1^2 = \frac{V_0^2}{R^2 + L^2 p^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

If $r = \infty$, that is, if the shunt is removed, it reduces to

$$I_1^2 = \frac{V_0^2}{R^2 + \left(L p - \frac{1}{C p}\right)^2} \quad . \quad . \quad . \quad . \quad (2)$$

In the case when $2\,C\,L\,p^2$ is greater than unity, the value of I_1 given by (2) is greater than the value given by (1). Hence the primary current is *increased* by throwing into circuit a suitable condenser. If $C\,L\,p^2 = 1$ the expression for the current is reduced to

$$I_1 = \frac{V}{R},$$

or the current has the greatest value it can have, and the inductance of the primary circuit is entirely annulled by the condenser.

Maxwell thus pointed out the condition for obtaining the maximum primary current and the reasons why the interposition of a condenser of suitable capacity increases the primary current, and hence increases the secondary electromotive force to the point of creating very considerable sparks between the secondary terminals.

§ 21. Mr. Apps' Large Induction Coils, the Polytechnic Coil, and Mr. Spottiswoode's Great Coil.—In the years since 1867, Mr. A. Apps has devoted great attention to the production of large induction coils, and has been the designer and constructor of some of the most powerful coils in existence. Mr. Apps began by making coils of single flat spirals of wire insulated by discs of insulating material, but finding this construction too expensive, he adopted a modified form of the sectional winding. In 1869 he built the large Polytechnic coil, sometime exhibited and used at the old Polytechnic Institution of London. The secondary wire of this coil was 150 miles in length. The diameter of the wire was ·014 of an inch, and it was silk-covered. This secondary wire was wound in grooves about $\frac{1}{8}$ of an inch in width and 200 in number. The iron core was a bundle of soft iron wire, 4in. in diameter, weighing 123lbs., and about 5ft. in length. The primary bobbin weighed 145lbs., and consisted of 6,000 turns of covered copper wire ·095 of an inch in diameter and 3,770 yards in length. The secondary bobbin when complete had an external diameter of 2ft. and a length of 4ft. 10in. The primary coil was insulated from the secondary coil by an ebonite tube. Excited by the current from 40 large Bunsen cells, this coil would give secondary sparks 29in. in length, and could in a few seconds charge 66 Leyden jars, each having 11 square feet of internal coated surface. The secondary discharge could pierce blocks of glass 5in. in thickness. The secondary sparks were of considerable thickness and apparent volume, and accompanied by a kind of flame. The next coil of any importance was an 18in. spark coil made for the late Mr. Spottiswoode, which was made on the same general lines as the Polytechnic coil. After introducing many improvements, Mr. Apps began, in 1876, to construct his most important induction coil, viz., the colossal induction coil built for the late Mr. Spottiswoode, which is described as follows in the *Philosophical Magazine* for January, 1877, p. 30, and which was used by Mr. Spottiswoode in many of his researches. It is thus described in the above-mentioned periodical by Mr. Spottiswoode himself:—

"The general appearance of the instrument is represented in Fig. 27, by which it is seen that the coil is supported by two

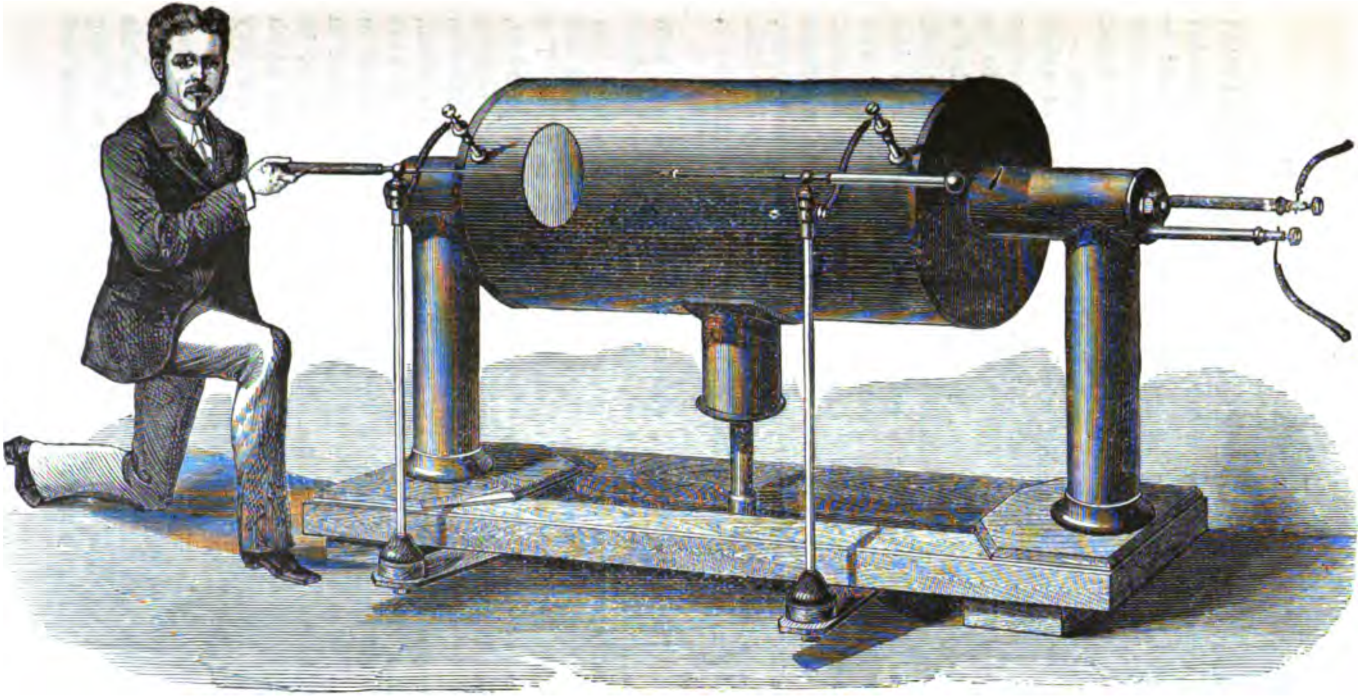

FIG. 27.—Mr. Spottiswoode's Great Induction Coil, made by Mr. Apps (1876).

massive pillars of wood, sheathed with gutta-percha, and filled in towards their upper extremities with paraffin wax. Besides these two main supports, a third, capable of being raised or lowered by means of a screw, is placed in the centre, in order to prevent any bending of the great superincumbent mass. The whole stands on a mahogany frame resting on castors.

"The coil is furnished with two primaries, either of which may be used at pleasure. Either may be replaced by the other by two men in the course of a few minutes. The one to be used for long sparks, and indeed for most experiments, has a core consisting of a bundle of iron wires, each ·032in. thick, and forming together a solid cylinder 44in. in length and 3·5625in. in diameter. Its weight is 67lbs. The copper wire used in this primary is 660 yards in length, ·096in. in diameter, has a conductivity of 93 per cent., and offers a total resistance of 2·3 ohms. It contains 1,344 turns wound singly in 6 layers, has a total length of 42in., with an internal diameter of 3·75in. and an external of 4·75in. The total weight of this wire is 55lbs.

"The other primary, which is intended to be used with batteries of greater surface, *e.g.*, for the production of short thick sparks, or for spectroscopic purposes, has a core of iron wires ·032in. thick, forming a solid cylinder 44in. long and 3·8125 in diameter. The weight of this core is 92lbs. The copper wire is similar to that in the primary first described, but it consists of 504 yards wound in double strand forming three pairs of layers, whose resistances are ·181, ·211, ·231 ohm respectively. Its length is 42in., its external diameter 5·5in., and its internal 4in. Its weight is 84lb. By a somewhat novel arrangement, these three layers may be used either in series as a wire of ·192in. thickness, or coupled together in threes as one of ·576in. thickness. It should, however, be added that, owing to the enormous strength of current which this is capable of carrying, and to the highly insulated secondary coil being possibly overcharged so as to fuse the wire, this larger primary is best adapted for use with secondary condensers of large surface, for spectrum-analysis, and for experiments with vacuum tubes in which it is desirable to produce a great volume of light of high intensity, as well as of long duration at a single discharge. The alternate discharges and flaming sparks can also be best produced by this primary. It has been used for high-tension sparks to 34in. in air, the battery being 10 cells of Grove's with platinum plates 6¼in. × 3in. Great facilities for the use of different sets of batteries are afforded by the division of this primary into three separate circuits, to be used together or separately; and by a suitable arrangement of automatic contact breakers, the primary currents may be made to follow in a certain order as to time, duration, and strength, with effects which, when observed in the revolving mirror, will doubtless lead to important results in the study of striæ in vacuum tubes.

"The secondary consists of no less than 280 miles of wire, forming a cylinder 37·5in. in length, 20in. in external and 9·5in. in internal diameter. Its conductivity is 94 per cent. and its total resistance is equal to 110,200 ohms. The whole is wound in four sections, the diameter of the wire used for the two central sections being ·0095in., and those of the two external being ·0115in. and ·0110in. respectively. The object of the increased thickness towards the extremities of the coil was to provide for the accumulated charge which that portion of the wire has to carry.

"Each of these sections was wound in flat discs; and the average number of layers in each disc is about 200, varying, however, with the different sizes of wire, &c. The total number of turns in the secondary is 341,850.

"The great length of the wire necessary can be easily understood from the fact that near the exterior diameter of the coil a single turn exceeds 5ft. in length. The spark, it is believed, is due to the number of turns of wire, rather than to its length, suitable insulation being preserved throughout the entire length. In order to ensure success, the layers were carefully tested separately and then in sets, and the results noted for comparison. In this way it was hoped that step by step safe progress would be made. As an extreme test, as many as 70 cells of Grove's have been used, with no damage whatever to the insulation.

"The condenser required for this coil proved to be much smaller than might at first have been expected. After a variety of experiments, it appeared that the most suitable size is that usually employed, by the same maker, with a 10-inch-spark coil—viz., 126 sheets of tinfoil 18in. × 8·25in. in surface, separated by two thicknesses of varnished paper, the two thicknesses measuring ·011in. The whole contains 252 sheets of paper 19in. × 9in. in surface.

"Using the smaller primary, this coil gave with five quart cells of Grove, a spark of 28in., with 10 similar cells one of 35in., and with 30 such cells one of 37·5in. and subsequently one of 42in. As these sparks were obtained without difficulty, it appears not improbable that, if the insulation of the ends of the secondary were carried further than at present, a still longer spark might be obtained. But special adaptations would be required for such an experiment, the spark of 42in. already so much exceeding the length of the secondary coil.

"When the discharging points are placed about an inch apart, a flowing discharge is obtained both at making and at breaking the primary circuit. The sound which accompanies this discharge implies that it is intermittent, the time and current spaces of which have not as yet been determined.

"With a 28in. spark, produced by five quart cells, a block of flint glass 3in. in thickness was in some instances pierced, in others both pierced and fractured, the fractured pieces being invariably flint glass. If we may estimate from this result, the 42in. spark would be capable of piercing a block 6in. in thickness.

"When used for vacuum tubes this coil gives illumination of extreme brilliancy and very long duration: with 20 to 30 cells and a slow-working mercury break, giving, say, 80 sparks per minute, the striæ last long enough for their forward and backward motion to be perceived directly by the unassisted eye. The appearance of the striæ when observed in a revolving mirror (as described in the *Proceedings of the Royal Society*, Vol. XXV., p. 73) was unprecedentedly vivid, and this even when only two or three cells were employed.

"Further experiments have shown that with such large coils only the newly discovered effects of very high temperature-combustion or volatilisation can be produced. On exciting the primary of the coil with a suitable dynamo-electric machine, or battery, and using a large Leyden jar in the secondary circuit (according to Sir William Grove's experiment), the electrical discharge passing between electrodes placed before the slit of the spectroscope lines and bands may be observed to advance and recede according to the variations made in the magnitude of the exciting discharges. As the atmospheric pressure may be assumed to remain constant, these effects are probably due to differences of temperature arising from the action of a greater or smaller extent of electrical effects on the electrodes in a given time."

Following on this great coil Mr. Apps has made many others, such as the 20in. spark coil made for the Framjee Kawasjee Institute of Bombay, and by certain devices of insulation has increased the length of the secondary spark beyond the length of the bobbin, thus making a bobbin of $8\frac{1}{2}$in. in length give an 11in. spark. As an illustration of this fact Mr. Apps has, by permission, furnished the author with the details of six coils made for Lord Armstrong, the measurements of which are as follows:—

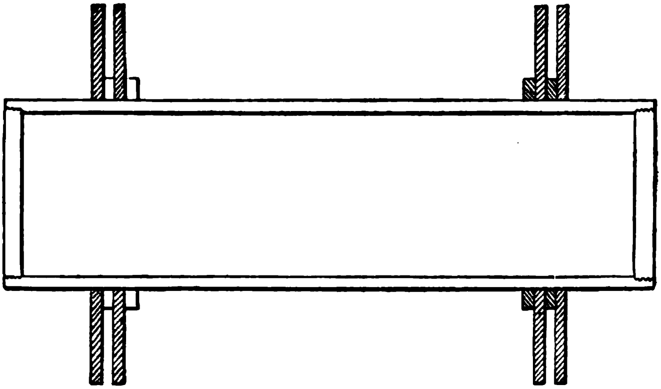

FIG. 28.—Apps's Method of Insulating the Secondary Coil.

The secondary circuit consists of 8 miles 25 yards of silk-covered copper wire, ·0064in. in diameter. It makes 41,425 turns, and weighs in all 7lbs. 1oz. 7drs. The secondary circuit resistance is 12,500 ohms. The interior diameter of the secondary bobbin is $3\frac{5}{16}$in., the exterior $5\frac{7}{16}$in., and the length $8\frac{5}{8}$in. The secondary spark is from $10\frac{1}{4}$in. to 11in. in length. The primary coils consist of square copper wire, No. 14 B.W.G., the length of wire on each bobbin being 51 yards, laid on in four layers of 366 turns. The primary coil resistance is ·32 ohm. The length of the primary coil is

9·1in.; the outside diameter of the bobbin is 2in., and the inside diameter 1·6in. The most effective primary current is a current of 12 amperes and 10 volts. Each coil is fitted with a condenser divided into six parts. The details of the processes by which these remarkable achievements in insulation are produced are of the nature of trade secrets, but generally it may be said that the greatest precautions have to be taken to secure the result. Mr. Apps has obtained a high reputation by the excellent performance of many of his coils.

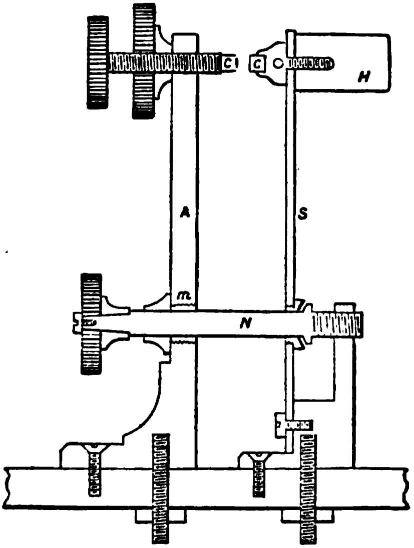

Fig. 29.—Apps's Improved Contact Breaker.

Some of Mr. Apps's improvements in induction coils are described in his British Specification, No. 177, of January 24, 1867. In this he gives the details of improvements in the mode of insulating the secondary coil, and in the construction of the contact breaker. His method of obtaining high insulation between the primary and secondary coil is as follows:—The primary coil is wholly enclosed in an ebonite tube (*see* Fig. 28), which projects beyond the secondary coil for some distance. On this ebonite tube are slipped, alternately, a series of ebonite discs and ebonite rings, which act as distance pieces separating the discs, and thus form a series of narrow grooves or compartments in which the secondary coil is wound. The secondary coil is then laid in these grooves, each section being carefully insulated and tested, and the several sections joined up so that no two portions of the wire which come very near to each other are at very different potentials. Besides greatly improving this groove mode of winding, Mr. Apps devoted attention to the contact breaker. He gave it the form shown in Fig. 29. In this figure S is the spring which carries the hammer head H. The pillar A is perforated and bushed at *m* with an insulating collar, and a tightening screw, N, serves to press back the hammer spring, if desired, so that the platinum contacts, *c*, *c*, are pressed more tightly in contact, and the time of vibration of the spring, S, is increased. This enables the rate of break to be altered even during the working of the coil. Mr. Apps has devised a form of multiple contact break which renders it possible to divide the break spark between several points.

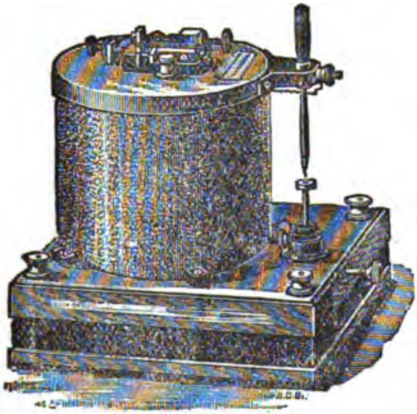

FIG. 30.—Pyke and Barnett's Induction Coil.

It cannot be said that any subsequent improvements have been made which have altered for the better the mode of construction adopted by Mr. Apps for the construction of the induction coil since his chief large coils have been made. Other makers have introduced little changes of arrangement, but the essential features in all good coils remain the same, and even the general form of the coil is not much varied. Some changes of manufacture have been introduced, such as that in Pyke and Barnett's induction coil (*see* Fig. 30). In this coil the hammer break is erected on the top of a vertically placed coil. The hammer is mounted on a short thick spring and is rapidly vibrated by an auxiliary electro-magnet, the exciting coils of which are in a shunt circuit to the main primary coil. The main coil contacts are so mounted that their normal position is in contact, one of them being carried on a spring. The vibrating hammer in its excursion strikes against one of these contacts and separates them slightly and instantaneously, thus interrupting the circuit of the primary coil.

The whole of the parts are arranged for ready and rapid adjustment. The discharging terminals of the secondary circuit are arranged at the side of the coil in a convenient manner.

§ **22. The Electro-technical Use of the Induction Coil. Shepard's and Whitehouse's Coils.**—The induction coils previously described were all devised and contrived with the object either of purely scientific applications or for the purpose of exalting the degree of the effects capable of being produced by the induction coil. Inventors began, however, to see in the induction coil an apparatus which might be applied for electrotechnical purposes, and to direct their attention to that side of its development. Hence began a long series of patents for improvements in induction coils, which have been growing, especially since 1878, at an ever increasing rate. One of the earliest of these patents was set out in a long and not very lucid specification of Floris Nollet, of Brussels, communicated through E. C. Shepard to the British Patent Office, dated No. 13,302 of 1850. The nature of Nollet's improvements is not very clear from his specification, but he seems to have had the idea of using the induced currents obtained from induction coils for the purpose of producing the electric light by some kind of arc or incandescent electric lamp. He employed in some cases flat spirals of thin metal as his primary or secondary circuits, and he interwound the two circuits in a manner afterwards proposed by Gaulard and Gibbs.

In 1855 Whitehouse obtained a British patent (No. 2,617 of 1855) in the specification of which occurs a description of induction coils applied for telegraphic purposes. It is entitled, "Improvements in electro-telegraphic apparatus, parts of which are also applicable to other purposes." One section of the specification is on "Improvements in induction coils." The secondary coil was to be placed nearest the iron core, and was surrounded by the primary. These coils were to be used singly or two or more in combination, all of them being included in the same primary circuit. The secondary currents thus obtained were stated to be applicable for telegraphic, blasting, ordnance, as well as electro-chemical purposes.

Edward and Charles Bright took out a British patent about this time, dated No. 2,103 of 1855, for "Improvements in telegraphic apparatus." In their specification the construction of certain induction coils is described, the arrangement being as follows:—The primary coil was wound on an iron rod and surrounded by an iron tube, both being in connection with the iron flanges of the coil. The secondary coils were to be wound outside the iron tube, and, if necessary, to be surrounded by another iron tube and an additional serving of the primary coil. It is not very clear in what respect this arrangement was considered to be an improvement, for it is certainly not an arrangement conducive to obtaining the greatest amount of inductive effect in the secondary circuit.

§ 23. Varley's Improvements in the Induction Coil.—Mr. Cromwell Fleetwood Varley obtained a British patent in 1856 (No. 3,059), in the long specification of which certain improvements in induction coils are described and claimed. These improved coils were to be applied for telegraphic purposes. The most remarkable change which Varley made in the construction of the induction coil was in making the iron core a "closed magnetic circuit." The soft iron wires intended for the core were cut more than three times the length of the bobbin. After the primary and secondary coils had been wound on the core the ends of the soft iron wires were bent back so as to overlie and enclose the windings (*see* Fig. 31) and thus complete the magnetic circuit. Varley also divided his coil into partitions by means of glass discs, winding the secondary coil in compartments and joining up the several coils so that no two adjacent parts of the wire were at very different potentials.

In winding his primary coils he proposed to use square sectioned wire as being more compact. He also proposed to interwind in some cases the primary and secondary coils. He devised an ingenious key for not merely breaking the primary circuit, but reversing the primary current in it at the instant of depressing the key. Varley maintained that by so doing he obtained a better effect. Although he was probably the first to construct an induction coil with a closed magnetic circuit combined with a divided iron core, he did not explicitly state that this form of core was not the most suitable for use with a simple interrupted current, on account of the superior magnetic retentiveness of such a circuit, but must necessarily be employed with a reversed or alternating current if the best results are to be obtained. Varley, however, constructed the coil in this manner, and was, as observed, probably the first to adopt a closed circuit divided iron core for an induction coil. Varley's

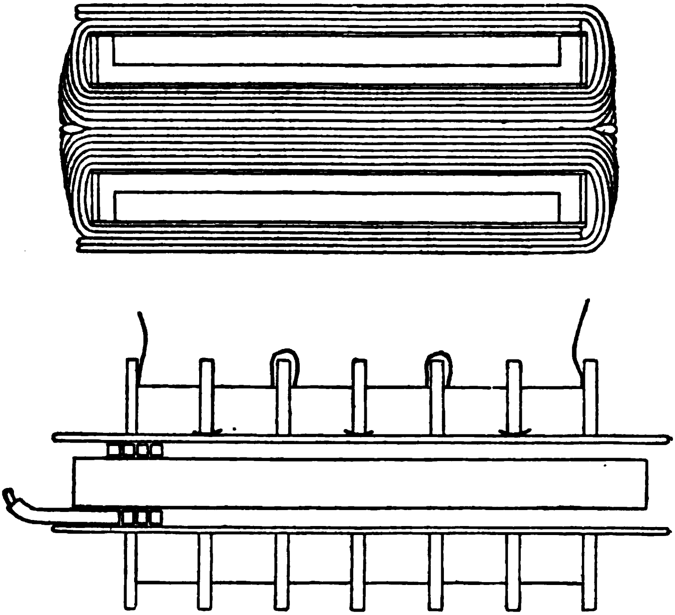

FIG. 31.—Varley's Induction Coil (1856), with closed-circuit divided Iron Core.

special claims in this specification as regards the induction coil are for "encasing induction coils with iron outside the primary or primary and secondary wires," and "placing a series of three or more flat induction coils side by side so as to place the secondary wire for the most part between two primary wires."

In 1857, C. W. Harrison obtained a patent (No. 588) for "improvements in obtaining light by electricity," in the specification of which he has a few remarks on the use of a secondary or induced current from an induction coil, with or without a condensing arrangement, in connection with a primary current to produce electric light. The primary current was to give motion to the electrodes and the secondary current to produce the electric light. He says "it is prefered not to break the circuit of the primary current, but to reverse it."

Morris, Weare, and Monckton patented in 1861 (No. 2,661), and in 1862 (No. 1,516), certain improvements in induction coils and applications of them to the production of light. The secondary discharges from induction coils were to be passed through vacuum tubes and illumination thus obtained. These inventors did not do more than enumerate and claim improvements previously made.

§ 24. Jablochkoff's Employment of Induction Coils.—In 1877, Paul Jablochkoff obtained a British patent, dated No. 1,996, May 22nd, 1877, for "a new process of producing and dividing the electric light and apparatus therefor." In this specification he describes and figures the use of a number of induction coils all having their primary coils arranged in series and traversed either by an interrupted direct current or by an alternating current, the secondary currents so induced being employed to maintain, in action, one or more electric lamps of a particular kind, these lamps being arranged in series. The lamps were described as giving light by the incandescence of a piece of kaolin interposed between two conducting electrodes. The object Jablochkoff had in view was to "divide the electric light," that is to say, to establish a number of small and independent units of light. This he considered he had done by the employment of a number of induction coils "placed on one and the same circuit," and each generating from one primary current a series of secondary currents employed to illuminate one or more electric lamps. He says in his specification: "As a great number of induction coils can be placed in the circuit, and as a number of lamps may be placed in the circuit of each coil, it will be seen that the electric light is thus capable of very great subdivision." The fact that the closing or opening of the secondary circuit of any one coil of such a series affects the primary current through all the rest does not at all appear to have been present to the mind of the inventor. An application for the extension of this British patent of Jablochkoff came before the Judicial Committee of the Privy Council in May, 1891, but was refused on various grounds (see *The Electrician*, May 15th, 1891, p. 52). During the hearing of this case it was pointed out that a communication describing fully Jablochkoff's system of electric lighting by induction coils had been made to the Society of Telegraph Engineers of London, on May 9th, 1877, or thirteen days before the date of his British specification.*

§ **25. British Patents for Improvements in Induction Coils granted in 1878.**—In 1878 numerous patents were applied for in England for improvements of one kind and another in the construction and technical use of induction coils. Wilde took out a patent (No. 1,228 of 1878) in which the alternating currents from one of his magneto-electric machines were to be passed through the primary coil of an induction apparatus, the secondary currents being employed for actuating telegraphic instruments.

C. W. Harrison in his specification (No. 3,470 of 1878) describes the employment of induction coils arranged in series and traversed by an alternating current of electricity, and the utilisation of the secondary currents of the coils for operating a rudimentary form of electric lamp.

C. T. Bright filed a provisional specification (No. 4,212 of 1878), in which secondary currents from induction coils were to be employed for producing light by means of discharges in rarefied gases. The primary coils were apparently intended to be placed in series with each other. Edwards and Normandy in their British specification (No. 4,611 of 1878) also re-patented the employment of induction coils, having their primary coils all arranged in one series and traversed by a rapidly intermittent current, as a means for generating local secondary currents to be applied to the production of light by the incandescence of metals and other materials. The use of alternating currents of electricity for the same purpose is also indicated. The secondary circuits were to be insulated wires or ribbons of metal or stranded conductors.

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* See *The Journal of the Society of Telegraph Engineers*, 1877, p. 306, "On a new form of Electric Light."

In a British patent (No. 5,183 of 1878), J. B. Fuller, of New York, travelled over very much the same ground as Jablochkoff. He defines the object of his invention as being to provide an electric light adapted to all purposes and divisible into small units. He constructed electro-magnets, consisting of two soft iron magnet cores, arranged parallel with each other and connected magnetically at the ends. These electro-magnets were to be wound over with two circuits, one a primary and the other a secondary, in two or more sections (*see* Fig. 32). The primary coils of different magnets were to be joined up in series with each other and to be traversed by an alternating current (*see* Fig. 33). The secondary coils then become the seat of induced currents, and

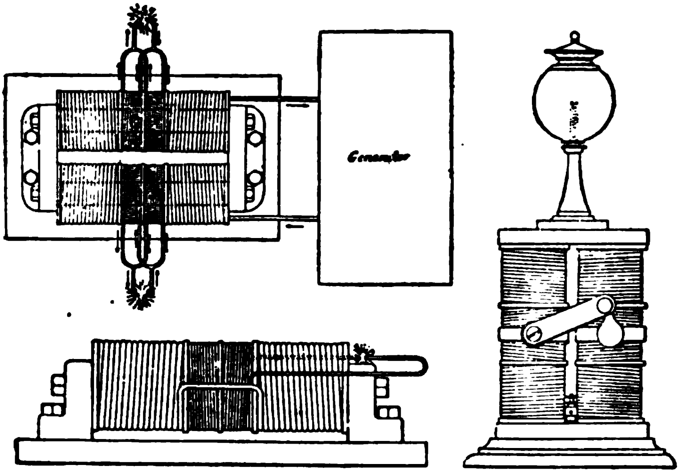

Fig. 32.—Fuller's Induction Coil or Transformer (1878).

these were to be utilised for the production of light by arc or incandescent lamps.

In the *Electrical Review* for April 1st, 1879 (Vol. VIII., p. 117), there is a further description of J. B. Fuller's mode of employing his induction coils. This inventor had evolved a whole system of lighting—the generator, a lamp, and a meter. He proposed to use two large street mains, one of them insulated, disconnected at the outward ends. The positive main was to throw off a branch wire into each building to be lighted, the wire entering the meter, performing a certain service there, and then returning to the negative main. The main current was not to do the lighting, but it was to generate another current in a series of induction coils, and each lamp was to be lighted by the current from one of these coils. An alternating current was to be used. This ardent and ingenious inventor died (February, 1879) before he could put his plans into action, but we have in the above-mentioned description of his work a plain statement of the proposed plan of placing a

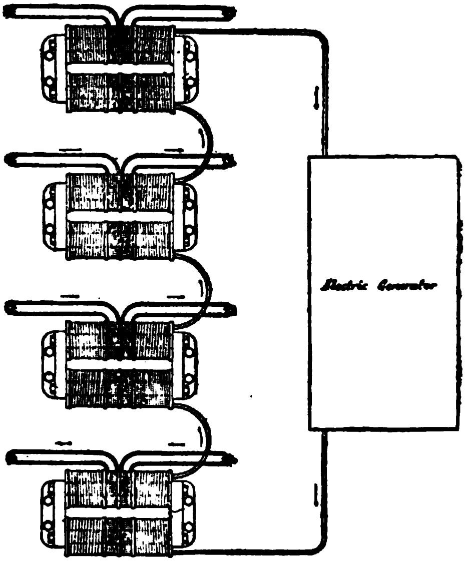

FIG. 33.—Arrangement of Fuller's Transformers in Series.

series of induction coils with primary coils *in parallel* between two main primary lines and operating lamps off the secondary circuit.

In a brief description of Fuller's induction coil, given in the *Electrical Review* for April 15th, 1879 (Vol. VII., p. 130), it is stated that Fuller proposed to connect together the secondary coils of his transformers in parallel or in series according to the requirements of the lamps to be used. In this article there is a drawing and description of Fuller's induction coil.

It is clear that Fuller, like Jablochkoff, had the notion that an alternating current could be passed through the primary coils of any number of induction coils arranged in series, and that the induction coils could be made to produce secondary currents at different places, and that each secondary current could be regulated independently of the rest. There is no mention that the iron cores are to be of divided iron, but the inventor recognised that different electromotive forces might be generated in the secondary coils, according to the degree of fineness of the wire employed and the number of convolutions of the secondary coils.

De Meritens obtained a British patent (No. 5,257 of 1878) for the same class of invention. He proposed to employ an alternating current which was to traverse the primary coils of a series of induction coils, and to generate, in as many coils as desired, secondary currents to be locally employed in producing electric light. The iron cores of the induction coils were to consist of bundles of soft iron wire, these cores being arranged in some cases so as to form nearly closed magnetic circuits. Every one of these inventors seem to have laid hold of the same erroneous idea, namely, that a single primary current could produce at different parts of its circuit any required number of distributed secondary currents by means of local induction coils, each of which could be regulated independently of the others and of the primary current. Poggendorff, as we have seen, had shown, experimentally, and Maxwell, in 1865, theoretically (*Phil. Trans. Roy. Soc.*, p. 459, 1865), that such would not be the case, and that the closing of any one secondary circuit reduced the impedance of the whole primary current, and conversely that the opening of any one secondary circuit increased the impedance of the whole primary circuit, and thereby affected the current flowing through all the other primary coils, and hence the secondary currents of all the other coils. The vicious notion that an unlimited number of induction coils could be independently operated by one and the same primary current, like a row of independent windmills by the same current of wind, seems to have been widely disseminated in the minds of inventors in the year 1878, and even at a later date was revived again by two more persevering pioneers.

§ 26. J. E. H. Gordon's use of Induction Coils.—In May, 1880, Mr. Gordon filed a British specification (No. 1,826) for apparatus for producing electric light. He proposed to take advantage of the fact already made known by Mr. Spottiswoode in 1877, and as we have seen, by Sir W. Grove previously in 1868, and many others, that the alternating currents of a magneto-electric machine could be employed to produce secondary currents by means of suitable induction coils. The currents from the secondary circuits of these coils were to be employed for producing electric light by using them to create discharges between terminals, knobs of platinum, or other infusible metals, enclosed in glass globes.

He says in his specification: "I use induction coils of moderate size and place a number of them on the circuit of the machine, *either in parallel circuit*, or in series, or in a combination of the two."

It is interesting to note, however, that, in Edison's British specification (No. 5,306 of 1878) at the end of the provisional specification, he makes a brief reference to the use of induction coils for electric lighting, and he says: "Induction coils when used should be placed with their primary coils *in a shunt* from the main conductors with current shifting devices, and the secondary currents developed by induction are used in the electric candles." Hence, Edison clearly explained the employment of induction coils having their primary circuits arranged in parallel, in a specification, which deals specially with electric lighting by incandescent lamps, also arranged in parallel.

Mr. Gordon, in his specification, gives details of the induction coils he would prefer to employ for the purpose of his method of illumination. They were ordinary Ruhmkorff coils, with divided iron cores built in sections, and operated by an alternating current from a De Meritens magneto-electric machine.

§ 27. **Desprez's Experiments in 1881.**—Marcel Desprez and Jules Carpentier filed a British specification in 1881 (No. 4,128) which deserves notice, in that they proposed to employ induction coils both for raising and lowering the pressure of a current. In other words, they proposed employing both *step-up* and *step-down* transformers. They say: "When a quantity current, proceeding, for instance, from one or more elements of a Bunsen battery, is passed through the large wire of a Ruhmkorff's coil, high tension currents are produced in the small wire, which can overcome a great resistance, and can consequently be conveyed to a considerable distance without appreciable loss of power. If this high tension current be then made to pass through the small wire of a second coil at the receiving station, it will induce a quantity current that will have nearly the same force as the quantity current acting on the first coil, and which can then be employed for motive power or other purposes. By this means it has been found possible to heat to redness a platinum wire situated at a distance of several thousand yards by means of two Bunsen's elements, whereas it would have required a very great number of elements to obtain the same result if the communication between the battery and the wire had been direct." In the eighth claim of the specification this method of using two induction coils to successively raise and lower the pressure of a current is claimed.

§ 28. **Gaulard and Gibbs Secondary Generators.**—The next specification in order of date connected with the technical use of induction coils is that of Gaulard and Gibbs (No. 4,362 of 1882). In its original form, and before it received amendment by disclaimer, this specification was remarkable for its emphatic repetition of the erroneous notions on the working of induction coils in series, previously prevalent. These inventors, like others who preceded them, had the idea that an alternating current could be passed through the primary circuits of "an unlimited number" of induction coils, and that it would create in each secondary an induced current, "without in any way modifying the value of the primary current." The inventors devised a form of induction coil (*see* Fig. 34) wound over with a stranded cable of seven insulated wires, the centre one being the primary, and the six others, united in series or in parallel, being the secondary circuit. A central sliding core of divided soft iron was designed to move in and out and regulate the induction.

An alternating current was to flow through the primary and excite an induced current in the secondary circuit. They then proposed to place one of these coils, say every 500 metres, upon a primary circuit 50 kilometres in length, and to obtain local secondary currents for electric lighting (*see* Fig. 35). The inventors were evidently under the impression that this was a novel arrangement, and in the original specification they claimed as new not only the special form of induction coil, but also the system of distribution and the said use of an alternating current with an unlimited number of induction coils. This specification was amended by disclaimer on April 19th, 1888, to claim only "the employment of an alternating current of high tension for the generation on a number of *secondary generators* (*e.g.*, induction coils) of induced currents, individually utilised either for the production of light or motive power."

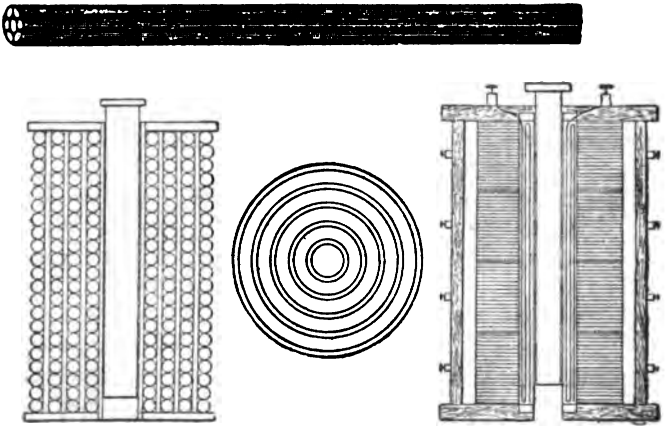

FIG. 34.—Gaulard and Gibbs First Induction Coil (1882).

The special form of induction coil was disclaimed. An attempt having been made to set up this patent as a master-patent covering generally the distribution of electric currents by means of induction coils or secondary generators, a plea for the annulment of this patent was presented, in the month of July, 1888, to the High Court of Justice,* and a revocation of the patent was granted and afterwards confirmed in the Court of Appeal and the House of Lords.

The chief ground of annulment of this patent was, broadly, that the disclaimer had removed the claim for the special form of induction coil, and by so doing had vitiated the patent and extended the scope of its claims. This decision as to annulment was subsequently upheld, and the patent, therefore, became void in 1890.

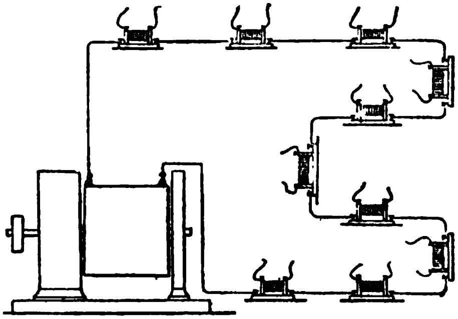

FIG. 35.—Arrangement of Gaulard and Gibbs Secondary Generators in Series.

The Gaulard and Gibbs Secondary Generators, as they were called, first came before the notice of the electrical world in 1883, at an Electrical Exhibition held at the Westminster Aquarium, in London. Two induction coils of the form shown in Fig. 36 were exhibited, by means of which electric lamps were lit by secondary currents. The primary current was a current of 13 amperes derived from a Siemens alternator, and one secondary generator yielded a secondary current of 40 amperes, lighting incandescent lamps, and the other provided current partly for incandescent lamps and partly for Jablochkoff arc candles, and for an alternating motor.*

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* *In re* Gaulard and Gibbs Patent (No. 4,362 of 1882). Heard before Mr. Justice Kekewich, July, 1888, and subsequently carried into the Court of Appeal in 1889, and to the House of Lords in 1890.

At the time when Gaulard and Gibbs exhibited these experiments, no one could be said to have any definite knowledge on the subject of the efficiency of an induction coil as an appliance

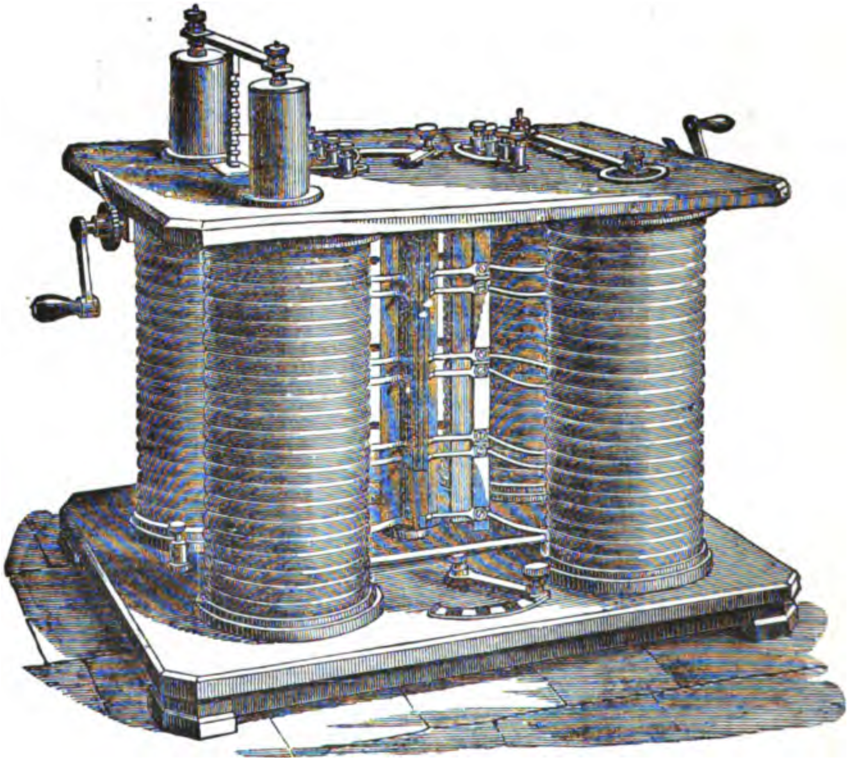

FIG. 36.—Gaulard and Gibbs Secondary Generator (1883).

for transforming energy. It was common knowledge that an induction coil could be used to transform electrical energy by raising or lowering the pressure of a current, changing a small current at high pressure into a larger current at lower pressure, but no one had even a rough idea of the amount of energy dissipated in this transformation. The general notion was that it was probably considerable. Hence, Gaulard and Gibbs deserve very great credit for the boldness and constancy with which they insisted on the practicability and efficiency of this method in face of a good deal of ridicule and doubt. They persevered, however, in pressing their method of electrical distribution on the attention of the world, although it was, of course, pointed out to them that Jablochkoff and Fuller had, at least on paper, carried the project quite as far. Not only did they engage in controversy with their opponents, but they made a further exhibition of their secondary generators on a larger scale.

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* See *Electrical Review*, April 21, 1883, Vol. XII., p. 325.

In the latter part of 1883, an experiment was tried on the Metropolitan Railway. A Siemens alternator was put down at the Edgware Road Station, and a high-pressure alternating current was led through the primary circuits of a series of secondary generators (*see* Fig. 37), which reduced the pressure. The high-pressure current was transmitted through the primary coils of secondary generators placed at Notting Hill Gate, Gower Street, King's Cross, and Aldgate stations. The length of the primary circuit was 16 miles, and the primary coils of the generators were placed in series upon it. Incandescent and arc lamps were worked at these various stations. Dr. Hopkinson reported on this system, and made use of the quadrant electrometer, in the manner suggested by Messrs. Ayrton, Fitzgerald, and Joubert, to obtain some measurements of the electrical efficiency of this system, and concluded his observations indicated an electrical efficiency of 86—89 per cent.* These results were criticised by some writers, and it was considered that this value was too high. M. Hospitalier, in particular, pointed out that the efficiency of transformation would decrease as the load on the secondary circuits decreased, and expressed the opinion that at half-load the efficiency would not be more than 50 per cent.

In the autumn of 1884, at an exhibition at Turin, another demonstration was made of the Gaulard and Gibbs system. In this case the primary circuit was nearly 50 miles in length, and had a total resistance of 130 ohms. In the Exhibition buildings stood a Siemens alternator, worked by a 30-H.P. engine. The primary line was a chrome bronze wire of high conductivity, 3·7 millimetres in thickness, and carried on insulators on posts. A series of secondary generators was

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* *See* Report of Dr. Hopkinson, *Electrical Review,* Vol. XIV., p. 262, March 29, 1884.

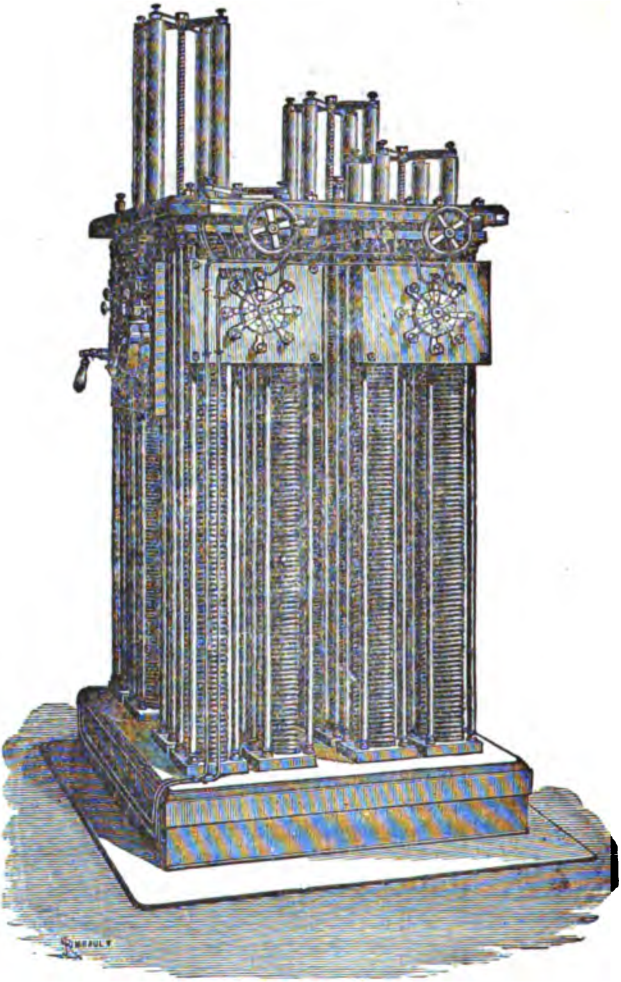

FIG. 37.—Gaulard and Gibbs Secondary Generators.

placed on this line, one being in the Exhibition buildings, one at the Turin railway station, another at the station Veneria

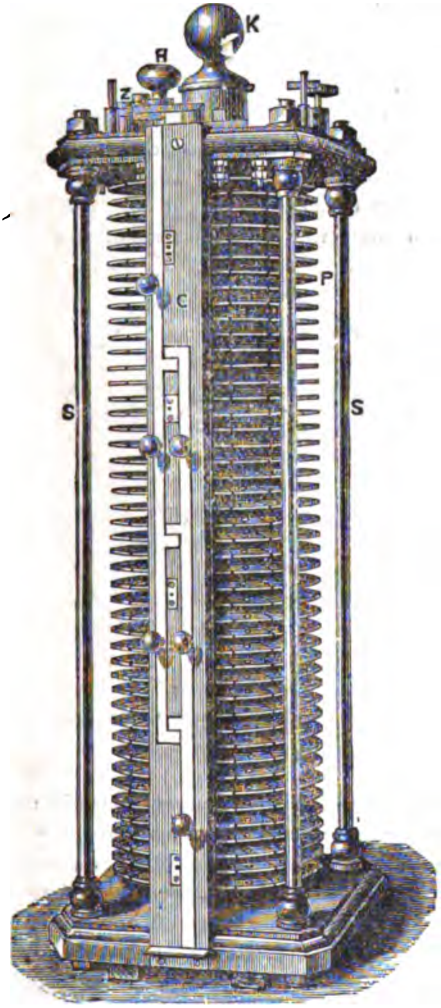

FIG. 38.—Gaulard and Gibbs Secondary Generator (1884).

Reale, and another at Lanzo, a small village in the Alps of Savoy. Incandescent and arc lamps were supplied at these various places. The secondary generator here employed is represented in Fig. 38, and consisted of a series of copper rings of a shape shown in Fig. 39; these were piled one above the other and insulated from each other. This construction of this secondary generator is described in the specification of Gaulard and Gibbs (No. 3,173 of 1884) in the following words: "According to our invention, we form the conductor for the primary current and the conductor in which the induced current is produced, of a series of annular discs, slit across at one part and furnished with ear-pieces at either side of the slit, the said ear-pieces extending from the outer circumference of the annular discs.

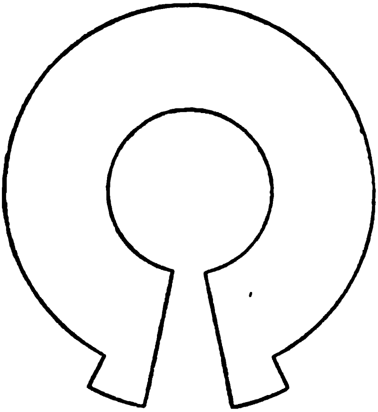

FIG. 39.—Ring or Disc of Gaulard and Gibbs Secondary Generator (1884).

The conductor for the primary current is made up of a series of these annular discs, and the conductor for the induced current is made up of another series of these annular discs, the two series being so interlaced that the convolutions of the helix formed by the discs for the primary current alternate with the convolutions of the helix formed by the discs of the induced circuit. An annular disc of insulating material is placed between each convolution of the double helix thus formed, and the ear-pieces of all the discs for the primary current are soldered together, and the ear-pieces of all the discs for the induced current circuit also soldered together. The double helix thus formed is provided with an iron core and completed as in an ordinary induction coil" (*see* Figs. 40 and 41).

A further specification for this mode of construction was filed in 1884, viz., No. 11,385 of 1884.

It is curious to note that Gaulard and Gibbs found that this arrangement of interlaced discs bestowed on the apparatus a

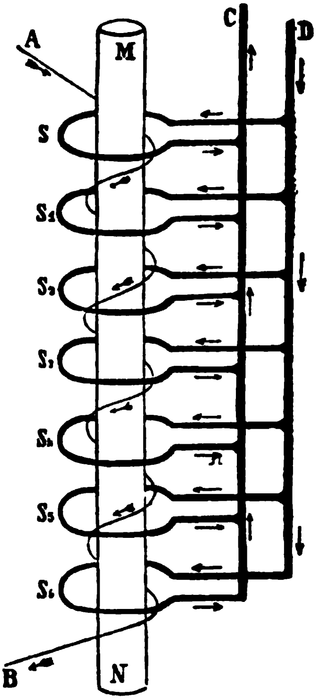

FIG. 40.—Diagram showing Mode of Connecting up Split Rings in the Gaulard and Gibbs Secondary Generator to form Primary and Secondary Circuits.

prejudicial electrostatic capacity, and to eliminate this quality they resorted to the old device of Callan and of Page, and joined together the primary and secondary circuits, only they effected this junction by the intermediation of a coil of high self-induction (*see* Fig. 42). This device is described in their specification, No. 11,331 of 1885.

Returning to the experiments at Turin Exhibition, we may note that the jury of the exhibition, including such authorities as Tresca, Weber, Ferrini, Ferraris, Wartmann, Voit, and Kittler, expressed themselves satisfied that a very novel and important experiment had been made in carrying current for lighting over such a distance by means of induction coils; and an award of 10,000 francs was granted to the inventors for further experiment. Prof. Galileo Ferraris began, during the exhibition, a long research on the efficiency of conversion of these induction coils, and the results of his work were fully described in the *Electrical Review* for 1885, Vol. XVI.* Prof. Ferraris confirmed the results of Dr. Hopkinson by showing that at full load the efficiency of such a transformer was in the neighbourhood of 86—89 per cent. M. Pietro Uzel carried out experiments at Turin† which also confirmed the above general results. He found the efficiency of a small Gaulard and Gibbs transformer to have a maximum value of

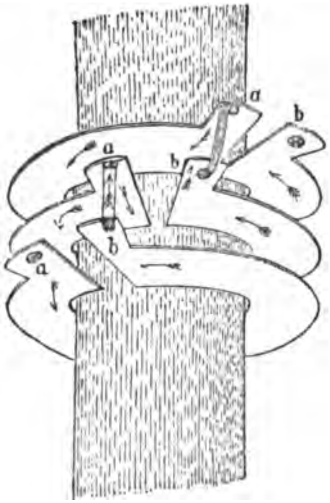

FIG. 41.—Diagram showing Mode of Connecting up Split Rings in Gaulard and Gibbs Secondary Generator to form a Spiral Circuit.

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* *See also* "Alternate Current Transformer," Vol. I., chap. 4, § 18, for a full account of Prof. Ferraris' work.

† See *Electrical Review*, Vol. XVI., p. 256, March 21, 1885.

80 per cent. when the load was about 400 watts; and that of a larger size to have about 90 per cent. when the load was some 800 watts or thereabouts. He found that the efficiency of transformation decreased both for lesser and for greater loads. Prof. Roiti also determined the full load efficiency, and found it to be 91 per cent. In these Turin experiments the frequency of the current was 134—that is, the number of complete alternations was 134. This critical examination by experts of these secondary generators had this important consequence, that it compelled the attention of electricians to the virtues and the defects of the system of transformer distribution, as illustrated by the apparatus of Messrs. Gaulard and Gibbs. To these inventors undoubtedly belongs the credit of having practically demonstrated to the world, even against great opposition, the merits and feasibility of transformer distribution of electric energy.

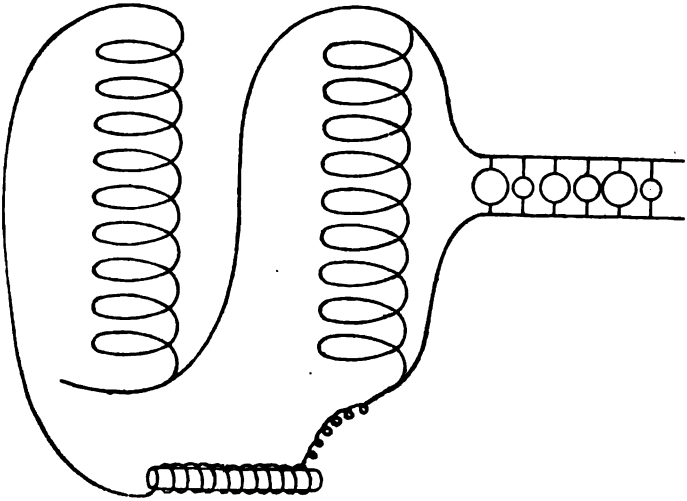

FIG. 42.—Gaulard and Gibbs Method of Annulling Capacity in Transformers.

It is a matter of historical curiosity, as illustrating the mysterious working of the official mind, that the United States Patent Office refused to grant a patent to Mr. A. Bernstein, in 1883, for the employment of transformers intended to lower pressure and increase current, and yet the same office granted a patent to Gaulard and Gibbs, in 1886, for the very same thing. Mr. Bernstein thus states his experience.* He says that in 1882, being then in Boston, U.S.A., he carried out a series of experiments with induction coils, and filed, in January, 1883, an application for a patent in the United States Patent Office for a transformer system, in which a high tension alternating current was to flow through the primary coils of a series of induction coils, and to be thereby transformed down into a number of independent low pressure currents. The application was rejected by the officials of the United States Patent Office, on the ground that "applicant should demonstrate more clearly to the office the possibility of producing quantity currents from intensity currents by means of an induction coil; it is not quite apparent how applicant in any case can get more quantity from a secondary coil than he has in his primary." Yet, in October, 1886, this same repository of official omniscience granted to Gaulard and Gibbs a United States patent, of which the first claim reads as follows :—

"(i.) The hereinbefore described art or method of electrical distribution and conversion, which consists in establishing in a closed electric circuit a current of alternate and equal positive and negative potential, producing by the influence of such a current an induction field of alternate polarity, and thereby inducing in translating devices situated in an independent closed circuit traversing such field a similar alternating secondary current *of greater quantity and less potential than the originating or producing current.*"

Will anyone say, after this, and having regard to Henry's experiments half a century before, that official wisdom is to be trusted in the matter of granting or refusing patents?

§ 29. **The Parallel Working of Transformers.**—The defects of the series system of arrangement of transformers made themselves evident during the practical trials of Gaulard's secondary generators on the Metropolitan Railway. Accordingly, even before that date, attention was drawn to the important advantages to be gained by arranging the primary coils of the transformer in parallel between two constant potential primary mains. In June, 1883, during the first exhibition of Gaulard's induction coils, Mr. Rankin Kennedy pointed out clearly the non-independent character of induction coils thus worked in series.* He described an experiment he had made illustrating the already well-known fact that the closing of the secondary circuit of an induction coil reduced the impedance of the primary circuit. This, as we have seen, had been experimentally demonstrated previously by Poggendorff, but was primarily proved by Faraday† from direct experiment, and shown by Maxwell in 1865 to be a consequence of first principles. Mr. Rankin Kennedy urged .the objections to the series arrangement of induction coils, and concluded that the arrangement of induction coils with primary coils in parallel between two constant potential loads would make the system of distribution self-governing. He failed, however, as far as can be judged from his letter in June, 1883, to the *Electrical Review*, to grasp the fact that the primary conductors could be made as small as required by sufficiently raising the primary electromotive force, and employing step-down or reducing transformers for lowering it in the secondary. There was no novelty in the simple parallel arrangement of induction coils, and transformers, even with primary coils arranged in parallel on a constant potential circuit, are not self-regulating, unless the lamps or energy-transforming devices are also arranged in parallel on the secondary circuits, and also unless the primary circuit of the transformer has such high impedance, when the secondary circuit is open, that the primary current is practically reduced to zero in consequence.

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* See *The Electrician*, Vol. XVIII., 1886, p. 60 and p. 566.

These principles may be rendered clear by considering the two systems of arrangement.

In Fig. 43 is represented a series of induction coils having their primary circuits in series. If incandescent lamps are arranged in parallel on the respective secondary circuits, then turning on the lamps of any one transformer will decrease the secondary circuit resistance for that particular transformer. This will decrease the impedance of the primary circuit, and will therefore increase the series current. Such a system cannot be made self-regulating, and changing the number of lamps in use on one transformer will always affect the current, and therefore the light, of all the other lamps. If the lamps on the secondary circuits are arranged in series, then, provided the

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* See *Electrical Review*, June 9, 1883, Vol. XII., p. 486.

† "Experimental Researches in Electricity," Vol. I., § 1,090 *et seq.*, Series IX.

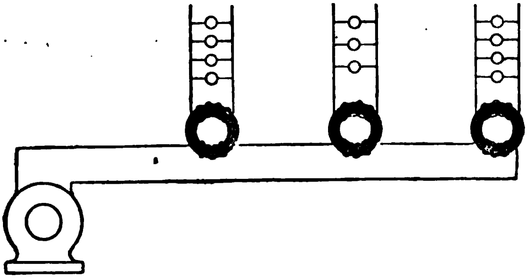

FIG. 43.—Transformers arranged in series, with Lamps in parallel.

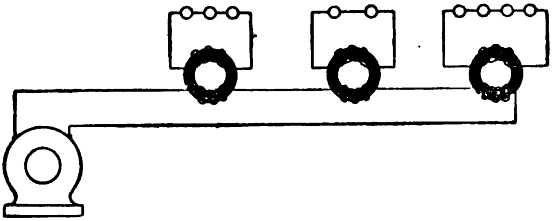

FIG. 44.—Transformers arranged in series, with Lamps in series.

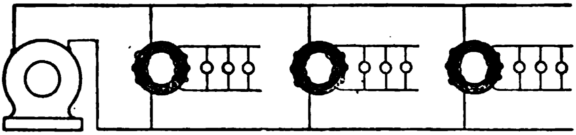

FIG. 45.—Transformers arranged in parallel, with Lamps in parallel.

primary current is supplied from a constant current alternator, so that the primary current is maintained constant for alteration of the impedance of the primary circuit over considerable limits, and provided also that the lamps or other devices are arranged in series on the secondary circuits, the system becomes a practical one, and is self-regulating and independent. Such an arrangement is shown in Fig. 44, and is further described in Chap. II.

Again, if the transformers are arranged with their primary circuits in parallel between two mains kept at a constant difference of potential, as suggested by J. B. Fuller in 1878, and if, moreover, the lamps are arranged in parallel on the secondary circuits, as in Fig. 45, then a second practicable system is obtained, provided also that the impedance of the primary circuit of each transformer when its secondary is open is great enough to practically block out nearly all current from the primary. On this constant potential system nearly all transformer distributions are now made. The peculiar advantages are that if the primary circuit of each transformer has sufficient impedance when on open secondary circuit, which can be secured by sufficient self-induction, then the transformer takes primary current just proportionately to the number of lamps turned on on the secondary circuit.

§ 30. **The Transformer System of Zipernowsky, Déri, and Bláthy.**—These advantages of the parallel constant potential system were not fully appreciated and acted upon until they had been definitely pointed out by Messrs. Zipernowsky, Déri, and Bláthy, of Budapest. In August, 1885, the investigations of these gentlemen were made known in a series of technical Papers,* and in which the reasons for adopting the parallel mode of arranging induction coils were given fully, as well as descriptions of transformers suitable for this method of working.

In the summer of 1885, the Inventions Exhibition was held at South Kensington, and part of the exhibit of the Edison and Swan United Electric Light Company consisted of a pair of 10 H.P. Zipernowsky-Déri transformers working in parallel between a pair of high-pressure leads, and reducing the pressure from 1,000 to 100 volts. The current for these transformers was supplied by a self-exciting alternator, and the primary current was conveyed by a pair of No. 10 B.W.G. insulated copper wires a distance of 800 yards to the place where the transformers were placed. This system was set in operation in London in July, 1885.* The transformers were closed magnetic circuit transformers, and the lamps were arranged on the secondary circuit in parallel. This was the first occasion on which transformers with their primary circuits arranged in parallel between a pair of constant potential high pressure mains were exhibited operating incandescent lamps, arranged in parallel on their secondary circuits. This small installation was worked throughout the summer and autumn of 1885 with perfect success. From and after this date the system of parallel working was universally adopted.

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* See *Electrical Review*, Vol. XVII., 1885, pp. 92, 114 140, 153.

In September, 1882, Messrs. Zipernowsky and Déri, of Budapest, first appear as British patentees taking out a patent (No. 4,535 of 1882) for "Dynamo Electric Machines." This specification relates to the construction of a self-exciting alternating current dynamo, in which a portion of the alternating current is rectified and utilised to excite the field magnets. The armature coils are fixed, and a stellate electro-magnet revolves in the centre, taking up current to energise it, which is shunted from the main current and rectified by a commutator. In July, 1884, the same inventors appear again in the British Patent Office lists as patentees (No. 9,982 of 1884) of what they call a "rotating secondary generator." This appliance consisted of an electric motor worked by a high tension current transmitted from a distant place, and an alternate or direct current dynamo combined with it; the windings for the motor and the generator part of the machine being on the same armature core. The object of this contrivance was to reduce electromotive force by causing one continuous current to generate another alternate or direct current at a lower pressure. In March, 1885, Messrs. Zipernowsky and Déri took out a British patent (No. 3,379 of 1885) for the system of arranging transformers as inductive coils, with their primary coils in parallel, and for a complete system of electrical distribution and the methods of regulation of pressure corresponding with it. The general scheme of their system of distribution was to form "secondary distributing stations," or "local centres," as they called them. In these centres were to be placed a group of transformers or induction coils having their primary circuits all arranged in parallel between two primary mains (*see* Fig. 46), and their secondary circuits all feeding in parallel into a common secondary network. The specification also provides means by which the pressure at the local centres on the primary mains can be kept constant by causing the electromotive force of the dynamo providing the primary pressure to be varied in accordance with the outgoing current in a manner fully described in § 5 of the next chapter. The third claim of this specification clearly describes the employment of low pressure networks fed by transformers, which reduce the pressure in a constant ratio

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* See *Electrical Review*, August 15, 1885, Vol. XVII., p. 153

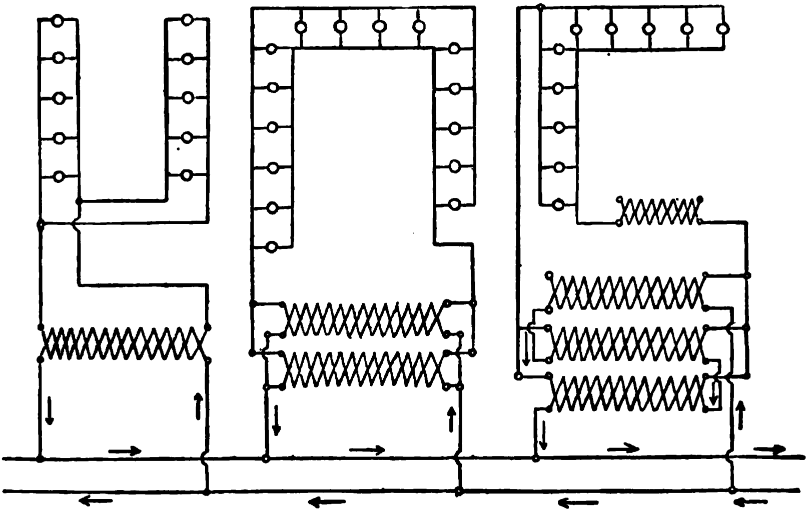

FIG. 46.—Zipernowsky-Déri Method of Arranging Transformers in parallel (1885).

from a primary circuit providing a constant high pressure service independent of load.

We come next to their British specification (No. 5,201 of April, 1885), in which Messrs. Zipernowsky, Déri, and Bláthy describe their first closed magnetic circuit secondary generator or transformer. Up to that date the advantages of using a closed magnetic circuit in alternate current transformers had not presented themselves to their minds, and they here describe the form which has been called the "life buoy" form of transformer. The primary and secondary circuits of this transformer were composed of circular coils of insulated wire overlaid one upon the other, and then the two together wrapped with iron wire, as shown in Fig. 47, which gives an elevation and section of the transformer. This form of transformer was, however, constructively and electrically an unadvantageous one, and in a short time ceased to be used.

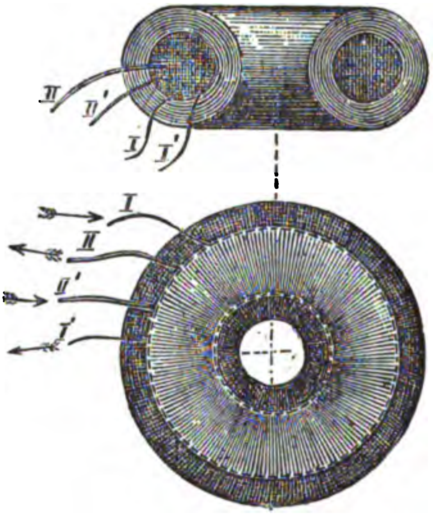

FIG. 47.—Zipernowsky-Déri Transformers, 1885 form (*See* Fig. 8, Chap. II., for perspective view of the same.)

§ 31. **Closed and Open Magnetic Circuit Transformers.**—We have seen that Cromwell Varley constructed induction coils in which the iron core formed a complete magnetic circuit linked with the conducting circuit, and that Zipernowsky and Déri later on constructed a dissimilar type of closed magnetic circuit transformer. Transformers or induction coils may accordingly be divided into four classes, depending on the disposition of the iron core. These are,

(i.) Transformers with open or incomplete iron magnetic circuits.
(ii.) Transformers with closed or complete iron magnetic circuits.
(iii.) The *core* type of transformer.
(iv.) The *shell* type of transformer.

The last two terms, *core* and *shell*, were introduced by Mr. G. Kapp, to denote the difference between transformers like that of Gaulard and Gibbs, in which the iron forms the core or central portion on which the wire windings are placed, and those in which the iron encloses the coils, like a shell, as in the 1885 Zipernowsky form. There are many forms of transformers which are as much shell as core transformers, and the divisions are not, therefore, sharply marked.

§ 32. Hopkinson's Patents for Transformers.—In 1881 Dr. Hopkinson took out a British patent (No. 3,362), in which he described the construction of a choking coil, constructed with a closed magnetic circuit of divided iron, wound over with coils of insulated wire (*see* Fig. 48). This was not designed as a transformer, but intended as an impedance coil for use with arc lamps for the purpose of steadying and regulating the current. It was intended that more or less of the coils should be thrown into circuit, as required, thereby constituting the device an adjustable self-induction coil.

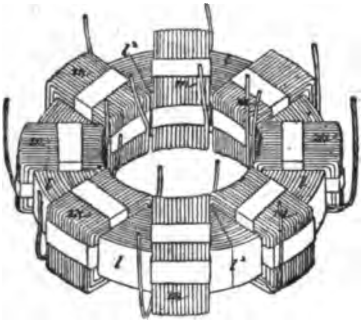

FIG. 48.—Hopkinson's Choking Coil (1881) with divided Iron Core.

In October, 1884, a specification was filed (No. 14,233), by John and Edward Hopkinson, for improvements in the construction and application of induction coils; and in this specification they proposed to construct secondary generators, having closed, or approximately closed, magnetic circuits of iron, divided parallel to the lines of magnetic force. The construction, as shown in Fig. 49, only differs from the previously patented choking coil in having two sets of circuits, primary and secondary, wound on the divided iron core. They claim that this improved induction coil possessed advantages over others, not only on account of its great power in comparison with its volume, but also on account of the small electrostatic capacity of the coils in relation to one another. The specification as originally drawn was evidently drafted on the presumption that such closed magnetic circuits of divided iron had not previously been used, but, as we have seen, Cromwell Varley had employed the closed divided iron circuit in an induction coil, and Hopkinson's patent was, therefore, amended by disclaimer on August 21st, 1890, leaving in claims covering the general construction of secondary generators with closed, or approximately closed, magnetic circuits of divided iron. Two forms are figured in the specification, in one of which the primary and secondary coils are wound on an iron core after the fashion of a Gramme ring, the primary and secondary coils being alternated and the secondary coils coupled up, either in parallel or in series, according to the purpose to be served. In the other form, the primary and secondary coils are placed on a straight core made of a bundle of iron wires, the magnetic circuit being completed by bundles of iron wires laid on outside

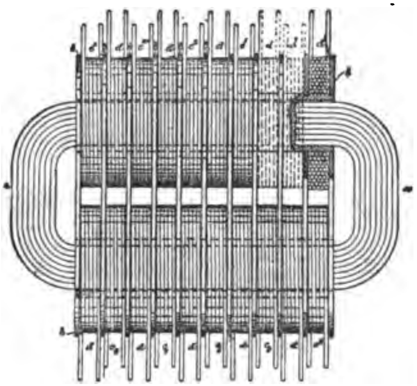

FIG. 49.—J. and E. Hopkinson's Transformer (1884).

the coils and brought into contact with the central core at the extremities, forming a closed induction coil resembling the arrangement of coil designed by Varley (*see* Fig. 50).

Prior to the date of Dr. Hopkinson's patent, Mr. Rankin Kennedy says he had employed, in an experiment, a closed magnetic circuit transformer having a core of divided iron. In a letter to the *Electrical Review*, on June 16, 1883 (Vol XII., p. 506), he describes the experiment he made with a Gramme ring, having a core of No. 16 B.W.G. soft iron wire, and having wound on it sixty sections of No. 14 copper wire. One half of these sections of the copper coils were connected up together in series, taking alternate coils, and the other half of the coils were also connected up in series. Then, using one series as a primary coil and the other as a secondary coil, he induced a secondary current by means of an alternating primary current. Some measurements of the ratio of the strengths of the primary and secondary currents of this 1 : 1 transformer led him to the conclusion that the Gramme ring so used formed an efficient secondary generator. He pointed out that the sections of this Gramme ring could be coupled up in series or in parallel.

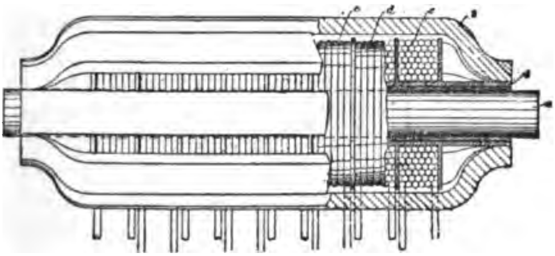

FIG. 50.—Hopkinson's Closed Magnetic Circuit Induction Coil (1884).

Gaulard and Gibbs also subsequently had suggested to them that it would be better to employ a complete iron magnetic circuit. Mr. Esson has stated* that, in 1885, he advised Gaulard and Gibbs to join up the cores of two secondary generators at the top and bottom, so as to complete the magnetic circuit.

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* *Proc. Inst. of Elec. Eng.*, Vol. XX., p. 202.

They acted upon this suggestion, and thus formed a Gramme ring as used by Kennedy. Mr. Bláthy has also asserted that, in August, 1884, experiments were in progress in Ganz's works at Budapest, which showed the advantages of a closed magnetic circuit of divided iron. We shall allude in a later chapter to the arguments for and against the open circuit type of transformer.

In connection with Hopkinson's patents, it may also be noticed that, in 1882, Dr. Hopkinson, in a British specification (No. 3,576), describes a method of measuring the potential at the end of a long service line, similar in principle to the methods afterwards employed by Zipernowski, Déri and Bláthy, which consisted in passing the main current, or a portion of the main current, through one coil of the galvanometer, the other coil being in a shunt across the mains (*see* Fig. 51). In Hopkinson's patent this method was only described in connection with continuous currents, but he applied the device not only to measure the pressure at the end of the long supply line, or feeder, but to preserve the pressure constant at the end of such feeder. This he proposed to accomplish by the use of a differentially wound relay, this relay being so adjusted that any variation in the pressure at the far end of the feeder could be made to alter the electromotive force of the dynamo attached to the feeder, by changing its magnetic field, or altering the speed of the motor in some convenient way. The circuits on the relay were respectively connected in shunt and in series with the circuit controlled.

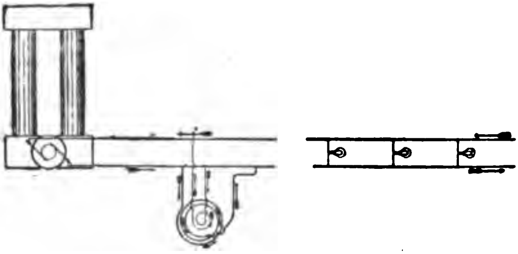

FIG. 51.—Hopkinson's Method of Measuring the Volts at the far end of a Feeder or Service Circuit.

§ 33. Further Improvements and Patents of Zipernowsky, Déri and Bláthy, in Transformer Systems and Transformer Construction.—In June, 1886, Messrs. Zipernowsky, Déri and Bláthy filed a British specification (No. 8,040), in which they developed, in a very comprehensive manner, a system of regulating the electric pressure at the extremities of the feeder lines, or long supply lines, taking advantage of the principle laid down in Hopkinson's patent just referred to, and which is explained more in detail in the next chapter. The object of the invention described in this specification is thus given by these inventors:—

"The object of this invention is to regulate the strength or the pressure of alternating electric currents by means of induction coils or transformers. One arrangement is intended to maintain a constant ratio between the intensities of alternating electric currents, having a common source, or to divide an alternating current of given intensity into two or more branches of determined strength. If two alternating currents from a common origin are sent in opposite directions through the two bobbins of an induction coil, this coil will have a tendency to bring the intensities of the two currents into a ratio to one another equal to the reciprocal value of the ratio of the number of windings of the respective bobbins; for in the bobbin in which there is the larger number of ampere-turns, there will be acting a counter-electromotive force, weakening the current, while in the second bobbin an electromotive force in the same direction as the current will tend to increase the current. The larger the mutual induction coefficient of the two bobbins, the less will be the difference between the ratio of the strengths of the two currents and the inverse ratio of the number of windings of the bobbins. Therefore, if we desire to have two alternating currents having a determined ratio to one another, we cause the currents to traverse the bobbins of an induction coil, the number of windings of the said bobbins being in a ratio to one another, the inverse of the current strengths required. In Fig. 52 is shown a system of distribution in which circuit I is such a divided circuit, and the induction coil D serves the purpose of maintaining the constant ratio in the strengths of the two branches of this circuit. The second method of applying transformers for the regulation of alternating currents is when alternating electric currents are distributed in a manner to maintain a constant pressure at the ends of certain conductors. In such cases, the inventors state they use transformers for compensating the fall of pressure caused by the resistances of the conductor between the points of consumption and supply, that is for automatically changing the pressure at the source of supply and keeping it constant at the point at which the current is to be used."

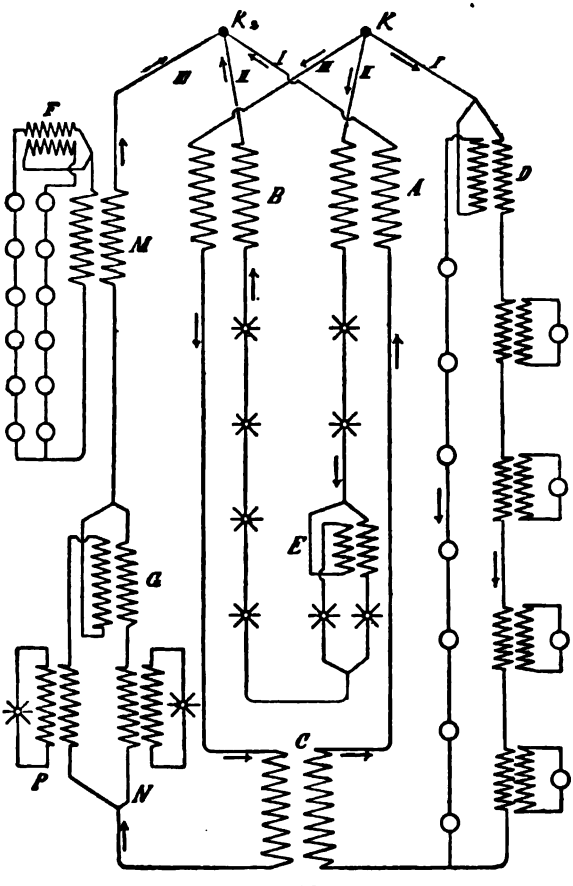

FIG. 52.

Broadly speaking, these regulating devices will be found to consist in the employment of transformers, one coil of which is in the main circuit, and another coil of which is a shunt across the main circuit, the currents being caused to flow in opposite directions round these two coils. Such devices are particularly useful in providing for the supply of constant pressure between branch circuits taken off at any point in the line of a long supply line of feeder, which is supplying current varying from time to time at a distant centre, at which centre

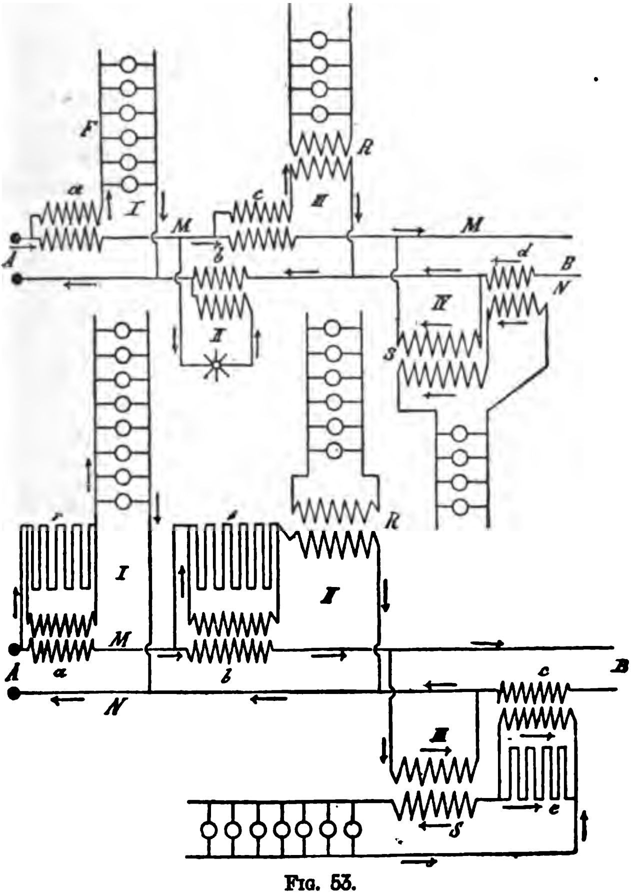

FIG. 53.

the pressure has to be maintained constant. Such an arrangement of transformers is shown in Fig. 53. One of the claims of this specification reads thus :—

"In distributing alternating electric currents with constant, or nearly constant, difference of potential in the conductors, the combination with the said conductors of induction coils or transformers, the one bobbin of which is inserted into the main conductor at or near the point where a branch current is to be derived from the same; this branch current, or the secondary current induced by it, in a transformer, passing through the second bobbin of the induction coil in the same direction with reference to the iron core as the main current through the first coil of that same transformer."

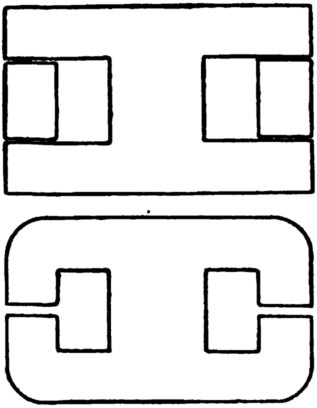

FIG. 54.—Sheet-iron Stampings for Zipernowsky-Déri Transformers (1887).

It will, therefore, be seen that, early in 1886, Messrs. Zipernowsky, Déri and Bláthy had worked out in detail a complete system of electric supply by transformers on the parallel system. Further reference will be made later on to these systems of distribution of alternating currents.

In 1887 they took out another patent, No. 395, in which they describe further improvements in the construction of transformers. Abandoning the old life-buoy shaped construction as not very convenient in manufacture, they adopted in the next place an iron core, composed of stampings of sheet iron of various shapes, built together so that when wound with a primary and secondary coil closed magnetic circuits were produced. In some cases they adopted stampings of the shape

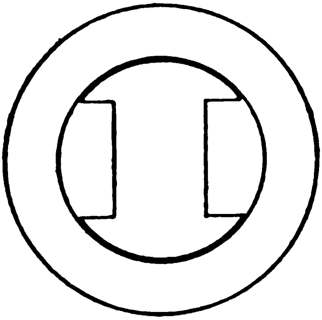

Fig. 55.—Shuttle-shaped Core and Ring for Zipernowski-Déri Transformer (1887).

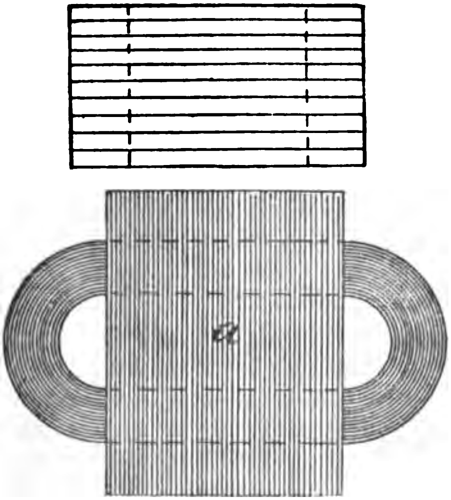

Fig. 56.—Zipernowski-Déri Transformer (1887).

shown in Fig. 54, built one upon the other, slits being left for the introduction of the wires, or piles of iron stampings being put in to fill up the gaps in the open ends of H-shaped iron stampings, over which the coils were wound. In other cases, they formed reels of iron tape wound up with tissue paper between the ribbon, and if a wide iron core had to be used, they preferred to form it from a number of narrow ribbons of iron, wound up together. Another form described by them in this specification consisted of a shuttle-shaped iron core, formed out of a pile of iron stampings, as shown in Figs. 55 and 56. The primary and secondary coils were wound on the recess in the shuttle-shaped core, and the magnetic circuit completed by surrounding the coils and the core by a pile of iron ring stampings, the whole being pressed together. In this manner the divided iron circuit was formed, laminated in a direction parallel to the lines of magnetic force. They afterwards again adopted a kind of Gramme ring of construction as described in Chap. II., but latterly, for greater convenience of manufacture and repair, they have returned once more to a construction which consists in putting together two sets of E-shaped stampings, having the primary and secondary coils wound on independent bobbins and slipped over the central core. The two sets of E-shaped stampings are kept in their proper position relatively to one another by means of strong round backplates, held together by transverse bolts.

Further specifications of Messrs. Zipernowsky, Déri and Bláthy, in 1887, 1888 and 1889, chiefly refer to the construction of alternating current dynamos and alternating current motors. The numbers of these British specifications are No. 17,812 of 1887, No. 12,856 of 1888, No. 12,858 of 1888, and No. 5,291 of 1889; the three last refer exclusively to improvements in alternating current motors.

§ 34. Rankin Kennedy's Improvements in Transformers.—Mr. Rankin Kennedy has taken out, since 1886, numerous specifications for improvements in the construction and application of the transformer. One of his earliest specifications, dated No. 12,531 of 1886, describes a transformer made with a shuttle-shaped iron core, very similar in construction, but anticipating in date, one form just referred to as designed by Zipernowsky, Déri and Bláthy. Mr. Rankin Kennedy constructed his shuttle-shaped iron core out of a pile of iron stampings, insulated from one another and pressed together, over which were wound the primary and secondary circuits (*see* Fig. 57). The

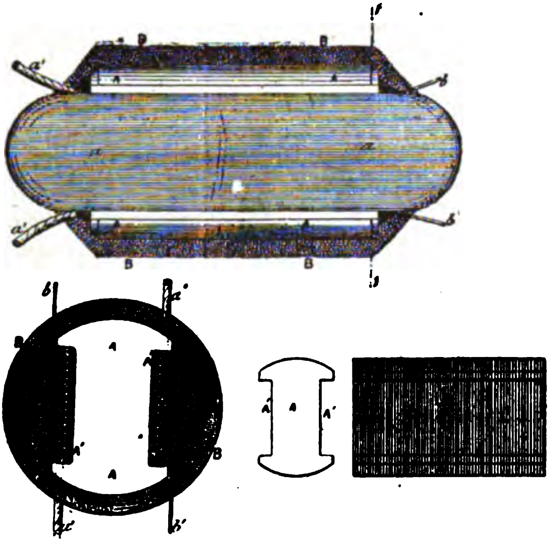

FIG. 57.—Rankin Kennedy's Shuttle Transformer (1886).

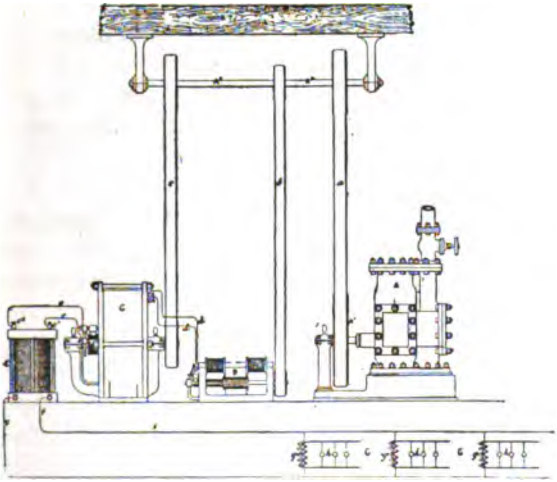

FIG. 58.—Rankin Kennedy's Step-up Transformer.

magnetic circuit was completed by winding iron wires over the shuttle-shaped iron coil, the direction of such windings being perpendicular to the axis of the core.

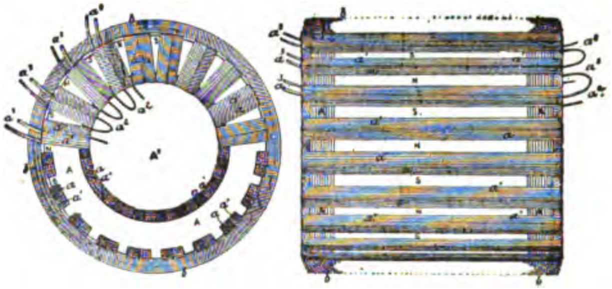

Fig. 59.—Rankin Kennedy's Pacinotti Ring Transformer (1886).

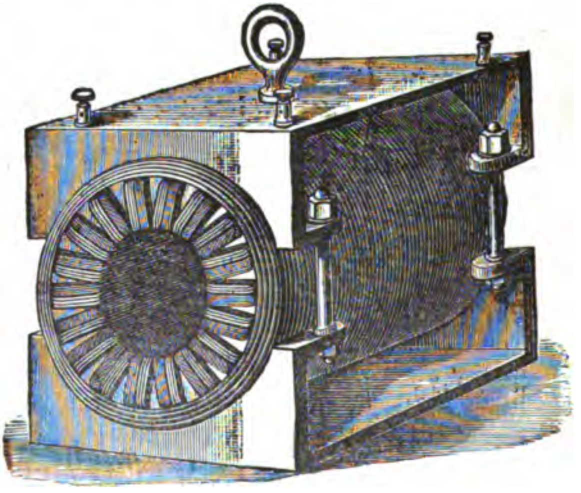

Fig. 60.—Rankin Kennedy's Pacinotti Ring Transformer (1886).

In 1886, Mr. Rankin Kennedy took out a British patent (No. 15,545) for a system of distribution, in which the alternating current was generated at a low pressure by means of alternating dynamos; the pressure was then to be raised by means of a group of station transformers, and a high pressure secondary current conducted to the locality at which they were to be used, and the pressure again reduced by means of local transformers (*see* Fig. 58). We have already seen that Marcel Desprez had employed induction coils both to raise and to lower the pressure of the current which is transmitted at a high pressure, in a similar manner, before this date.

In 1886, Mr. Rankin Kennedy patented other forms of transformers (No. 16,201 of 1886), in which closed iron circuits were employed, such circuits being wound over with primary and secondary circuits. In one form, the number of ring-shaped iron stampings having teeth upon them were piled together, so as to form a Pacinotti armature ring; in the intervals between these teeth the coils were wound, the whole being wound over with iron wire, so as to close the several magnetic circuits (*see* Figs. 59 and 60). The claim made for these improvements in transformers was that they bestowed upon the transformer a large coefficient of self-induction when on open circuit; in other words, they were improvements directed towards the construction of induction coils in which magnetising currents, when the transformer was on open secondary

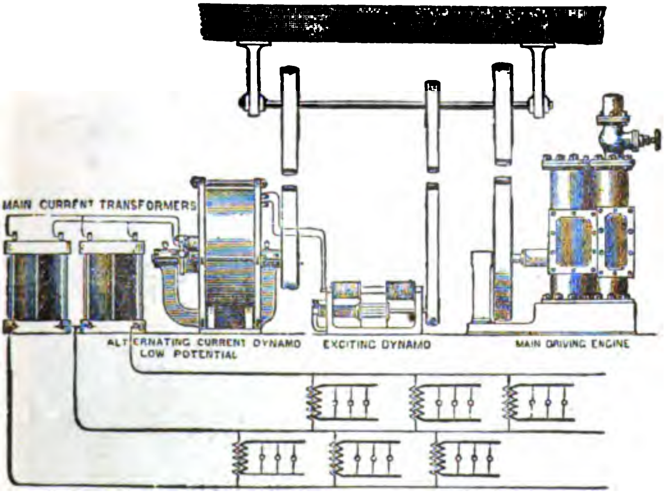
MAIN CURRENT TRANSFORMERS
ALTERNATING CURRENT DYNAMO LOW POTENTIAL
EXCITING DYNAMO
MAIN DRIVING ENGINE

FIG. 61.—Rankin Kennedy's Three-wire System, with Step-up Transformers.

circuit, should be very small, or in which, as the patentee expressed it, the self-induction should be the maximum, and should be useful and effective in rendering the secondary generator so constructed self-regulating.

In 1886, Mr. Rankin Kennedy patented (No. 16,326 of 1886) a system of three-wire distribution, by means of transformers, in which alternating dynamos supply the power to transformers operating a three-wire system (*see* Fig. 61). He also included an arrangement in which high pressure alternating current dynamos were worked directly on a three-wire system of circuits (*see* Fig. 62).

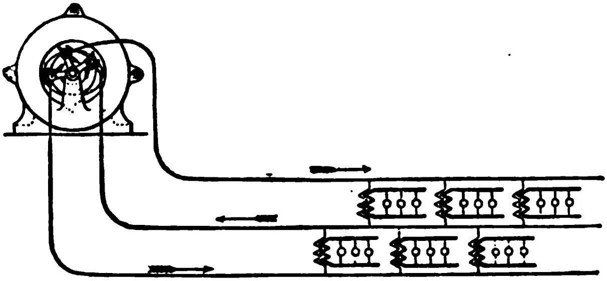

Fig. 62.—Rankin Kennedy's Three-wire Alternate Current System.

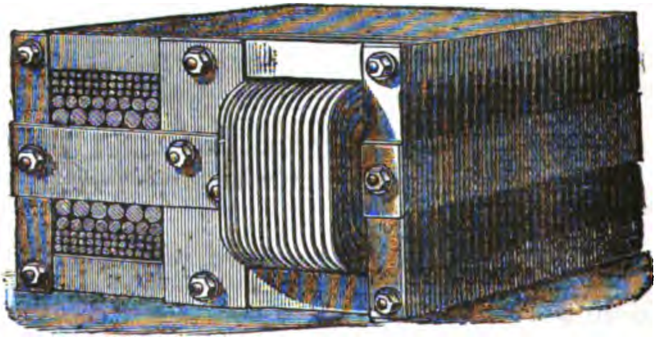

Fig. 63.—Rankin Kennedy's Transformer (1887).

In 1887, the same patentee filed a specification (No. 3,658), in which other forms (*see* Fig. 63) of transformers are described, characterised by arrangements which the patentee considered would reduce the energy losses owing to the magnetisation and demagnetisation of iron. This he proposed to do by means of a continuous constant current passing through a third coil on the transformer, the object of which was to maintain permanent magnetisation in the iron core. Apart, however, from the energy which would be dissipated by this constant current, the device would not achieve that which the inventor no doubt supposed it would, of entirely annulling the energy losses due to the hysteresis of the iron; for the creation of a secondary current all depends essentially on a change of induction in the core, and this change of induction involves loss by hysteresis, whether that change be a reversal of magnetisation, or only an increase and a decrease.

§ 35. Mr. S. Z. de Ferranti's Improvements in Transformers.—In December, 1885, at the close of the year in which the parallel working of closed magnetic circuit transformers had been exhibited in London, Mr. Ferranti filed a specification for "Improvements in Electrical Converters" (No. 15,141 of 1885), in which he described modes of constructing the transformer, which were a considerable improvement on existing forms. He employed an iron core, made up of narrow strips of iron about 1in. wide, and $\frac{1}{32}$in. thick, covered with paper on one side. A bundle of such strips is taken and taped together by shellac varnished tape in the middle of its length. Over the central portion of this bundle is then placed a coil or coils of thick insulated copper tape wire or band, which forms the low pressure circuit, and over these, and carefully insulated from them, another series of highly-insulated coils which form the high-pressure circuit. The extended portions of the iron strips or bands are then bent back, half of the strips in one direction and half in the other, and folded over, so that when pressed together each strip forms a closed loop interlinked with all the primary and secondary coils, as shown in Figs. 64 and 65. The iron bands are pressed together and kept in place by a cast iron frame of suitable form. This construction of induction coil will be seen to be similar to that of Varley in its general nature. Further details will be given of these transformers in the special description of the Ferranti system in the following chapter.

Two days after the filing of the specification for these transformers, Mr. Ferranti took out another British patent (No.

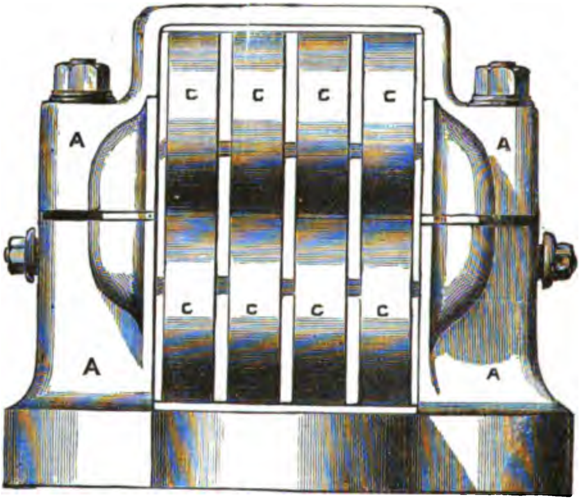

Fig. 64.—Ferranti Transformer.

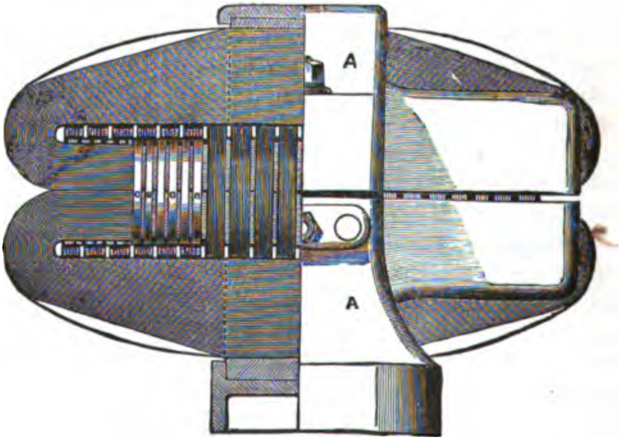

Fig. 65.—Section of Ferranti Transformer.

15,251 of 11th December, 1885), exceedingly comprehensive in the variety and extent of its claims, but which was broadly intended to cover a complete system of transformer distribution. This system is that which is now generally called the sub-centre system. Instead of employing a single transformer to supply current for each small group of lamps or motors on the premises of each consumer, the proposal is made to supply a system of mains laid on the parallel system with current from the secondary circuits of a number of transformers grouped in one convenient place. The primary coils of these transformers are connected in parallel between a pair of high pressure primary circuits. This arrangement constitutes a "sub-centre." By means of automatic switches the transformers are to be switched on or off the high pressure and low pressure circuits as the demand for current varies. Further reference will be made to this system of working, but it will be seen that the patentee had realized at this date clearly the serious loss of efficiency of distribution which results from supplying distributed transformers all the twenty-four hours with current, which passes through the primary circuits even when the secondary circuits are open, in virtue of the fact that the primary circuit impedance cannot be made infinitely great. In common parlance there is the all-day loss of magnetising current. The only way to eliminate this loss is to disconnect the transformers when they are not furnishing secondary current.

The same specification includes devices for constructing concentric conductors, consisting of two copper tubes one inside the other; also for automatic devices for indicating "earth" on either conductor. There are 10 claims in all to this specification. The special claim to the system of sub-centre working is the first, and reads thus:—"The improved means for distributing electric energy, consisting in providing high tension mains and low tension mains, and causing each low tension main to be fed from the high tension main, through one or more converters, which are connected and disconnected as required."

§ 36. The Modern Transformer since 1885.—Since 1885 very considerable improvements have been made in the design of the transformer and its construction. These improvements have been in the direction of so modifying the induction coil as to make it available as a means of reducing or raising electromotive force or currents in any constant ratio when it is employed with alternating currents. Transformers are called *constant potential transformers* when intended to raise or reduce electric pressure in any given constant ratio. They are called *constant current transformers* when intended to reduce current strength in any given constant ratio. The first is far more widely used than the second. With respect to the first-named form, we may say that an ideal constant potential transformer would be one which complied with the following conditions:—

1. That when the primary circuit has its terminals connected to primary mains between which exists a constant difference of potential, it should exhibit always a constant difference of potential between its secondary terminals, independent of the secondary load, and greater or less than that between the primary mains in a determined constant ratio called the *change-ratio* of the transformer. In the one case the transformer is called a *step-up* transformer, and in the other case a *step-down* transformer.
2. There should be no waste of energy other than that due to the resistance of the conductors or circuits.
3. There should be perfect and permanent insulation between the primary and secondary coils and between both coils and the iron core.
4. There should be no sensible electrostatic capacity between the primary and secondary coils.
5. When the transformer has its secondary circuit open, no sensible current should flow through the primary circuit from the primary mains.
6. The loss of energy in transformation should be as small as possible at all loads.

No actual transformer complies with these requirements in full. Actual constant potential transformers are more or less defective in having (i.) A variable change-ratio, (ii.) Energy losses in the iron core, (iii.) Greater or less imperfection of insulation, (iv.) Sensible electrostatic capacity, (v.) Current flowing through the primary circuit and energy losses in the core when the secondary circuit is open, and (vi.) Diminished, and often greatly diminished, efficiency of energy transformation when the secondary current is diminished by reason of increase of external secondary resistance.

The causes of these defects may be briefly enumerated as follows :—

The change-ratio of many forms of transformer is dependent on the electrostatic capacity of the secondary circuit, and is affected either in the way of increase or decrease by alteration of that capacity. This will be more fully discussed in a later section. The change-ratio of the transformer is affected by the changing load on the secondary. This is due to one or both of two causes: either to magnetic leakage, or to that combined with the potential drop due to the resistance of the secondary coil of the transformer. The lines of magnetic force, or, more correctly, of induction, which are generated by the primary current flow round in the iron circuit. The opposing current generated in the secondary circuit, being in almost complete opposition to the primary current in phase, creates an opposing magnetising force acting on the core. If we imagine the primary and secondary circuits to be wound separately and on opposite sides of a ring core (*see* Fig. 66), it is not difficult to see that the result of alternating currents, nearly opposed as they are in phase, flowing in the two circuits, is to partly neutralise the induction in the core in the part enclosed by the secondary coil, and to strengthen it in

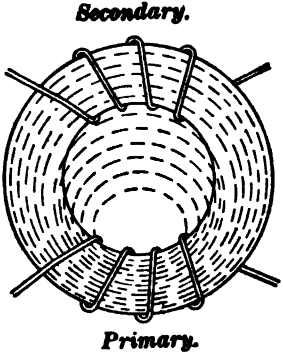

FIG. 66.—Diagram illustrating Magnetic Leakage in a Transformer.

the air-space in the interior of the core. Putting it in another way, we may say that every line of induction generated by the primary current does not link itself with the secondary circuit, but some lines are refused admission to the secondary circuit and leak across from side to side of the core. These lines are lost as far as creating electromotive force in the secondary circuit is concerned, and are called the *waste magnetic field.* This waste field is greater, the greater the secondary current. Hence it follows that between full secondary load and no load there is a fall in secondary electromotive force, called the "drop due to waste field," always assuming a constant primary electromotive force. This drop due to magnetic leakage can be reduced to a small amount by winding the secondary coils closely up amongst, and sandwiched with, the primary coils; and in all well-designed transformers this "drop due to leakage" should be kept within 2 per cent. of the full load potential difference of the secondary terminals. In addition to this, we have another action at work to diminish the potential difference between the secondary terminals, and that which is due to the resistance of the secondary circuit, or to the internal secondary resistance. This acts to reduce the potential difference between the secondary terminals as the external secondary circuit resistance decreases, or in proportion as lamps or load is put on when those lamps are arranged in multiple arc on the secondary circuit. This fall in potential difference is called the "drop due to resistance," and hence, as the secondary circuit of a constant potential transformer is loaded up with lamps in parallel, there is a diminution in the potential difference of the secondary terminals, partly due to drop due to leakage, and partly due to drop due to resistance, and, in properly designed transformers, this total drop should certainly not exceed 3 or 4 per cent. of the full load difference of potential between the secondary terminals.

It is never possible to quite annul all drop in individual transformers, but, by attention to design, the leakage drop can be made very small, and, by reducing the internal resistance of the secondary circuit, or by making the resistance of the secondary circuit small, the drop due to resistance can be kept within the necessary limits. In the next place, modern transformers are designed with the object of making the energy losses in the transformer as small as possible. These energy losses are partly due to dissipation of energy in the copper coils, called the *copper losses*, or C^2R losses, and partly due to losses in the iron due to magnetic hysteresis and eddy currents, and called the *iron losses*.

The eddy current losses may be kept small by a proper lamination of the iron, and by interposing thin paper, oxide paint, or some equivalent insulation, between the thin strips or plates of iron. It does not appear, however, that this loss can be quite annulled by any amount of lamination. The hysteresis losses cannot be abolished by any degree of sub-division of the iron, but are inherent in the use of iron itself as a core. These magnetic hysteresis losses are the principal source of the inefficiency of transformers at low loads, or when no secondary current is being taken out of the transformer. One of the chief directions which research should take is to discover some means by which these hysteresis losses in the iron can be reduced to a negligible quantity, whilst still retaining the use of an iron core on account of its quality as a superior conductor for lines of magnetic force. This matter will be dealt with more fully in a later chapter. The next element of imperfection is the failure of insulation between the high and low pressure coils. The various methods of insulation in use are described in connection with the various forms of transformers in other sections; but, generally, we may say that the insulation and separation of the high and low pressure coils is effected by the employment of such materials as shellaced cloth, asbestos, mica, ebonite, india-rubber, vulcanised fibre, porcelain, or preferably by means of fluid dielectrics, such as resin oil or heavy insulating oils of various characters. One cause of rupture of the insulation is an electric spark or arc between some point on the high pressure primary coil and the low pressure coil, or between the high pressure coil and the iron core. In the case of very high pressure currents a sort of glow discharge may first be formed, which afterwards breaks into an arc at one point. Also coils, either on the high or low pressure side, may become short circuited, and thus form electric arcs or short-circuits, destroying the insulation. Even if an internal arc is not formed, the short-circuiting of coils will give rise to internal heat, perhaps carbonising the insulation and bringing about a failure of the transformer. Attention has been paid again, recently, to the question of insulating by means of fluid insulators, as originally carried out and suggested by Jean and Poggendorff. The advantages which a fluid insulator is supposed to possess are, that when the transformer is wholly immersed in it all air and moisture are excluded, the formation even at very high pressures of glow discharges is greatly prevented, and, even if a spark does pass, unless the oil is decomposed so as to form a conducting bridge of carbon, the insulation will generally be restored again on the cessation of the spark. Oil insulation was for many years advocated by the late Mr. David Brooks, and has been employed for transformer insulation by Messrs Johnson and Phillips, in England; Mr. Brown, of Oerlikon, in Switzerland; and the Thomson-Houston Company, in America. When oil is used the transformer must be enclosed in an iron or stoneware case, and, after this is very carefully dried and baked, the oil is poured in hot so as to exclude all air bubbles and moisture. The particular quality of oil employed has to be the subject of examination and test. The oil must be altogether free from water or acid, and should be heavier than water and as little inflammable as possible. Heavy resin oil meets these requirements when properly prepared. Generally speaking, air-spaces should not be relied upon for insulation. Air, although in one sense a very perfect dielectric, is yet a treacherous one. When two conducting surfaces are at different potentials, say, of some hundreds of volts, and insulated by air, a very great tendency exists for the dark discharge or glow discharge which is formed between these surfaces to pass into an arc. An exceedingly small electric spark passed between such surfaces will determine the formation of an electric arc, and under considerable alternating pressures the formation of an arc appears to be promoted by the smallest opportunity for surface conductivity of the dielectric, such as that afforded by the deteriorated surface of ebonite under the action of air and light. Fibrous materials, such as cotton or linen, saturated with shellac varnish, are very hygroscopic, and although when freshly prepared may insulate well, yet are very liable to deterioration with age and exposure to air. The available insulating materials are not numerous, and, in addition, their mechanical qualities are not very good. Probably the insulation of the future will be found in some liquid or combination of liquids highly insulating, not decomposable by heat or a small spark, and applied so as to assist in getting rid of the heat generated in the transformer coils and core.

Sensible electrostatic capacity is a quality of a transformer which is disadvantageous. Considering that a transformer consists of two metallic conductors separated from each other by a dielectric, whilst yet in close contiguity, it is obvious that such an arrangement must form a condenser, and will have some sensible electrical capacity. The approximate electrostatic capacity of a transformer between the primary and secondary coils is easily measured by insulating the transformer on blocks of paraffin wax and then taking a wire from one end of the primary coil and from one end of the secondary coil, the other ends being well insulated, and determining the capacity existing between these conductors, in the usual manner, by means of a ballistic galvanometer, battery, key, and standard condenser. Employing a standard one-third of a microfarad condenser, the author determined the capacity of a series of transformers of 2·5, 5, 10, 15, 20, and 100 horse-power, of a kind much used, and found the following values in fractions of a microfarad :—

Transformer Tested.	Electrostatic Capacity in Microfarads.
2·5 H.P.	·0039 to ·003
5 ,,	·0043 ,, ·0034
10 ,,	·0097 ,, ·0085
15 ,,	·0235 ,, ·03
20 ,,	·033 ,, ·03
100 ,,	·0026

Hence the capacity varied from $\frac{1}{30}$th to $\frac{1}{300}$th of a microfarad. These numbers will give an idea of the magnitude of capacity found, but of course every different construction of transformer will have a different value in this respect.

In September, 1885, Dr. J. Hopkinson called attention* to the danger which may arise from the employment of transformers of high electrostatic capacity. The primary circuit is raised, either as a whole or in part, to a high potential which alternates from *plus* to *minus* rapidly. If the transformer is being worked with its primary coil in series with others on a high tension series circuit, then the primary coil, as a whole, is raised and lowered in potential at each alternation. The electrostatic induction between the primary and secondary coils then causes the secondary coil and circuit, if insulated, to be similarly raised and lowered, and anyone touching the secondary circuit would, if standing on the ground, be traversed by a current and receive a shock, which would be proportional in magnitude to the capacity of the transformer, the frequency of the current, and to the potential of the primary circuit at that point. This condenser current would be, therefore, a current of high potential, and it might amount to a quantity sufficient to severely injure or kill the person touching the secondary circuit. Information is wanting to show what current is in any particular case dangerous, but it is improbable that any person could receive even one third or one-half of an ampere through vital organs without its causing fatal consequences.

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* *Phil. Mag.*, September, 1885, p. 292.

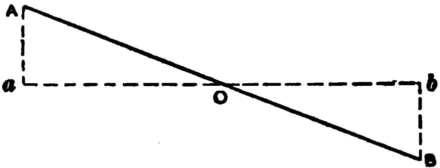

FIG. 67.

If the transformer is arranged with others on a constant potential circuit, and if we assume, in the first instance, that both primary and secondary circuits are insulated, then a different state of things exists. Each terminal of the primary circuit is alternately raised and lowered in pressure, and we can represent the state of each point on the primary circuit as regards potential by representing it as the ordinate of a straight line which rocks about its centre (*see* Fig. 67). The rise and fall of each extremity of the rocking line above or below the horizontal datum line represents the rise and fall in pressure at each end of the primary circuit. If, then, the secondary circuit is entirely insulated, the potential of this circuit, as a whole, will not be raised or lowered, because one end of the primary is at any instant as much above the earth's potential as the other is below it, and accordingly the secondary circuit will not be raised or lowered when taken altogether. Imagine, however, that one end of the primary circuit is put to earth and kept at zero potential, then the state of various points of the primary as regards potential may be represented by the ordinates of a line which rocks about one end (*see* Fig. 68). In this case the amplitude of motion of the extremity of the line is just double that of the extremity of the line rocking about its centre for equal angular displacements, showing that when one end of the primary is "earthed" the mean potential of the free end is double that which it would be if both ends were insulated. Under the circumstances the secondary circuit would receive a condenser charge, and anyone touching the secondary circuit, and at the same time making a "good earth," would receive a discharge current of high potential. This condenser discharge could be drawn off harmlessly by "earthing" one end of the secondary circuit, viz., that in proximity to the earthed primary end. The arguments *pro* and *con.* for these "earthing" and fully insulated systems will be discussed under the head of "Transformer Systems" in the third chapter.

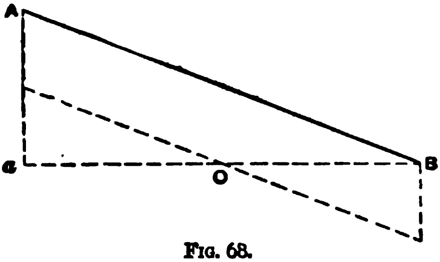

FIG. 68.

The next matter in which the actual transformer falls short of the ideal is in insufficiency of the primary circuit self-induction on open secondary circuit. This causes a very sensible current to flow through the primary, even when the secondary circuit is open. This current is commonly spoken of as the "magnetising current" of the transformer. The only way in which the magnetising current can be kept small, without undue increase in the resistance of primary circuit, is by increasing the self-induction of that circuit, or by increasing the frequency of the alternations. There are practical reasons against increasing the frequency beyond a certain limit, and there are difficulties of construction in increasing the self-induction over and above a certain point. On this point more will be said presently. Meanwhile we may say that a due attention to the arrangement of the iron core and the primary winding, combined with the selection of a suitable frequency at which to work, enables a constructor to devise a form of transformer which, for closed magnetic circuit transformers at least, is characterised by having magnetising current not exceeding three or four per cent. of the full load primary current.

Lastly, actual transformers in use are more or less imperfect transformers of energy when employed at less than full load. Very approximately the matter may be put in the following way:—The total losses of energy in a transformer are made up of the losses in the copper circuits, primary and secondary, and the losses in the iron core. There is very good reason to believe that the iron losses are less at full load than at no load, whilst of course the copper losses are greater. Supposing, as a first rough approximation, that we take the total losses in the transformer to be a constant quantity at all loads, the diminution in iron losses being compensated by increase in the copper losses, then the efficiency of transformation is the ratio of the electrical power delivered to the external secondary circuit to the electrical power delivered to the primary circuit. Accordingly the efficiency of transformation must be less at low loads than at full load, because the constant loss becomes a larger and larger fraction of the total power supplied, as that total power itself is diminished. Hence, arises a decrease of efficiency as the secondary load decreases.

This is represented generally by an efficiency curve in which the horizontal distances represent the load in watts on the external secondary circuit, and the vertical ordinates represent the percentage of the electrical power supplied to the primary circuit which appears in the external secondary circuit (*see* Fig. 10, Chap. II.). If transformers were always used at their maximum efficiency, then the practical efficiency of the device as an energy-transforming apparatus would be perfectly fixed by this one figure. This, however, is not the case. In one mode of electrical distribution by transformers, called the "distributed transformer" system, each customer or user is supplied with current for use for lighting purposes in his own premises from a transformer which supplies his own light alone. Under these circumstances, not only is it usual to put him in a rather larger size of transformer than his average requirements, to meet his wants on exceptional occasions, but he takes from that transformer his maximum current only for a very short portion of the twenty-four hours. Hence the *all-day* or *all-year* efficiency of the transformer is a very much smaller fraction than the maximum efficiency. The *all-year* efficiency of a transformer is defined to be the ratio expressed as a percentage between the energy given out by the transformer to the secondary circuit, which is what is paid for by the consumer, and the total energy supplied to the transformer from the primary circuit. The *all-day* efficiency can be calculated from the efficiency curve and from the *diurnal load diagram* of that transformer in the manner shown in § 4 of the next chapter. How far the above-named defects and disabilities of the transformer are overcome will be seen in the detailed description of the transformers as described under the various systems in use in following sections.

§ 37. Open and Closed Magnetic Circuit Transformers. The "Hedgehog" Transformer.—In the development of the transformer for the particular purpose of electric lighting by means of local distributed transformers, it is, as we have seen, of importance that a transformer should have not only a high maximum efficiency but a high average or all-year efficiency, and this can only be secured by a relatively high efficiency at low secondary loads. Of late years, controversy has arisen as to the relative merits of open and closed magnetic iron circuits in bestowing a high mean efficiency upon the transformer. Mr. J. Swinburne has advocated strongly a return to the open-circuit type of transformer as a remedy for a low all-year efficiency. He has devoted himself to designing a form of transformer, for which he claims advantages in this respect. This transformer, which he calls a "Hedgehog," is made with a core of soft iron wires, which are splayed or spread out at the ends, like a thistle head. The object of this is to reduce the magnetic resistance of the magnetic circuit. The general form of this transformer is shown in Fig. 69. The inventor remarks that, by the employment of an open iron circuit, he makes it obviously possible to reduce the volume of the iron with a given induction. The mean length of the iron part of the magnetic circuit being less, more copper turns can be wound on without increasing much the length of the iron part of the magnetic circuit. Hence the loss in the iron is reduced, but that in the copper is made rather greater. The loss in the iron tells most against the efficiency of the transformer at low loads. The construction of this transformer is stated to be as follows :—A gun-metal casting forms the backbone of the transformer. It is cross-shape in section, and at one end is spread out to form four legs. It also supports the lower flange, or cheek, of the winding. The four spaces have bundles of soft iron wire put in, so that the core is practically cylindrical. The cross-shaped core has been criticised on the ground that there are Foucault currents in it. The least consideration will show that there is no change of induction in it, and therefore no Foucault currents. The iron wire is bound tightly, and the two flanges are slipped into place. A gun-metal "spider" is then screwed to the top. It is finally held on by the eye-bolt, but temporarily a set screw is used. The core is then wound in a special lathe in the usual way.

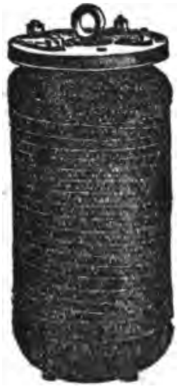

FIG. 69.—Swinburne's "Hedgehog" Transformer.

The electrical particulars of a 50 8-candle-power lamp transformer are as follows:—

Core, 13·5in. long, 2·5in. diameter. In taking the area of the core, allowance must be made for the space occupied by the backbone, and for the loss of room in using round wires. Maximum induction, 4,800. Loss of power in iron, assuming it to be of good quality, 13·5 watts. Primary, 3,920 turns of copper wire, 0·042in. diameter; resistance, 37 ohms (warm).

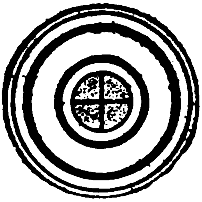

FIG. 70.

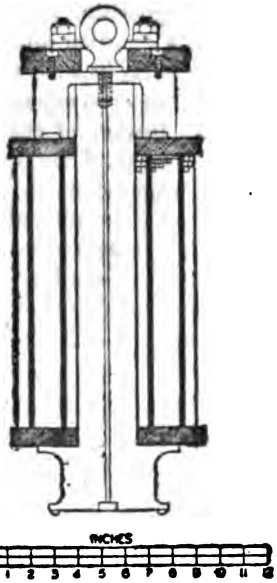

FIG. 71.—Sections of "Hedgehog" Transformer.

Secondary, 200 turns, 19/0·042in.; resistance, 0·098 ohm. Loss of power in primary at full load, due to the transformed current, 21 watts; loss due to the exciting current—0·3 ampere —which is always on, 3·6 watts; loss in secondary at full load, 22 watts. Efficiency at full load, 96·15.

This transformer is shown to scale in Figs. 70 and 71.

It is admitted that an open-circuit transformer of this kind has a magnetising current considerably in excess of that of a closed-circuit transformer of equal output. In the practical use of many transformers on a distribution system this becomes a serious matter, involving larger conductors, and lowering the "plant efficiency" of the system. The practical question is whether the gain in all-year efficiency is worth such additional expenditure in primary current taken on open secondary circuit, or in magnetising current. At present the materials for settling this question are not to hand. Arguments *pro* and *con.* are useless in such a case. The question at issue is whether such an open-circuit transformer has, on the whole, a less total dissipation of energy in itself during a year of use than a transformer of the closed-magnetic circuit kind of equal maximum output similarly used. This question can only be decided by a careful comparison of the efficiency curves of two such similar transformers, and this has not yet been done. We shall discuss in a later chapter some further questions arising out of the differences between the performance of open and closed magnetic-circuit transformers.

CHAPTER II.

THE DISTRIBUTION OF ELECTRICAL ENERGY BY TRANSFORMERS.

§ 1. **Transformer Systems.**—The employment of the alternate-current transformer for electric-current distribution has changed in many respects the practical possibilities of the supply of electric energy for lighting purposes in large towns and in districts in which great distances, comparatively speaking, separate the centres of consumption and supply. By its aid it has become possible to deal with problems in electric distribution which are less amenable, or perhaps, commercially speaking, unprofitable, when attacked by other methods; * and its enormous extension in six or seven years in Europe and in America is in itself evidence of the utility of the method. In examining the results as a whole that have been obtained by the employment and adaptation of the transformer for this purpose, we shall proceed to describe the principal systems at work, and the details of the installations of transformer systems in typical places in which it has established itself as a fit solution of the practical difficulties which there presented themselves to be overcome. The systems now occupying positions of importance, and on the lines of which, in different places, electric distributions of varying degrees of magnitude are being carried out, are chiefly those connected with the names of Ganz and Co., of Budapest, operating the methods of Messrs. Zipernowsky, Déri, and Bláthy; the Westinghouse Electric Lighting Company, and the Thomson-Houston Electric Lighting Company, in the United States, operating the systems elaborated by the well-known inventors connected with them; in England, the now familiar systems of the London Electric Supply Corporation (Mr. S. Z. de Ferranti), the Brush Electrical Engineering Corporation (Mr. Mordey), and the House-to-House Electric Light Supply Company (Messrs. Lowrie and Hall). The Metropolitan Electric Supply Company of London, employing for the most part methods and machines of the Westinghouse Electric Light Company, as well as Elwell-Parker dynamos and transformers, may be considered as a connecting link between English and American ideas. This list by no means exhausts the names of designers or manufacturers of transformers, or of its necessary adjunct, the alternating dynamo. Apart from efforts of pioneers we have excellent designs for these separate elements connected also with the

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* The arguments *pro* and *con.* in the case of alternate transformers and secondary batteries for central station electric lighting need not be entered into here; but we refer the reader to Mr. R. E. Crompton's excellent Paper, and the discussion thereon, in the *Journal of the Institution of Electrical Engineers*, Vol. XVII., 1888, and *The Electrician*, Vol. XX., pp. 634, 655, 694, 749, and Vol. XXI., pp. 88, 177.

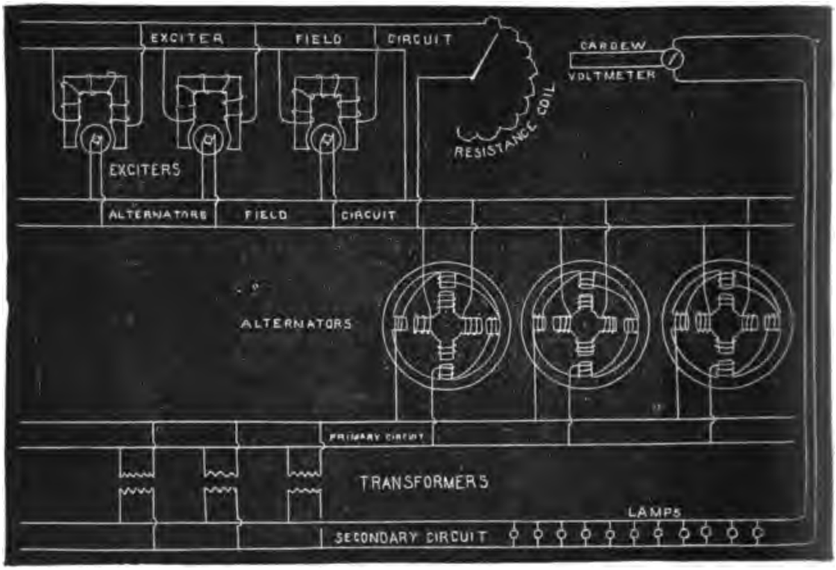


FIG. 1.—Arrangement of Alternators, Exciters, and Transformers in the Ganz System of Electrical Distribution.

names of Messrs. Siemens, Gramme, Hopkinson, Goolden, Kapp, Wilde, Snell, Swinburne, Sharp and Kent, Elwell-Parker, R. Kennedy, and many others; but the above-named six or seven complete systems comprise for the most part the best known apparatus in wide use for the distribution of electric energy by transformers; and some account of the machines, appliances, and methods in use by each respectively, taking typical examples, will now be given. The order in which they will be mentioned has, however, no reference to their historical order of development, nor to their relative importance.

§ 2. **System of Ganz (Zipernowsky, Déri and Bláthy).**—The methods of transformer distribution which have been elaborated and put into execution by the inventive ability of Messrs. C. Zipernowsky, M. Déri and O. T. Bláthy, of Budapest, have enabled the great firm of Ganz and Co. to establish a special electric lighting department and to undertake on a large scale the production of all the appliances and details which have been worked out into the complete system which bears their name. Nearly seventy central stations of different degrees of magnitude have been set in operation by them up to the present time (1890), in which electric energy is distributed to arc and incandescent lamps from central stations, about 1,000 arcs and 100,000 incandescents in all being supplied. The elements of this system comprise (i.) An alternating-current dynamo machine; (ii.) An exciting continuous-current dynamo; (iii.) The alternating transformers; and (iv.) Special regulating devices, which have for their object the maintenance of a constant pressure, irrespective of consumption, at some point or points in the distributing system. The system may be described as a *parallel* system in its entirety,—that is to say, the exciting dynamos are arranged in parallel between two exciting mains, the field-magnets of the alternating-dynamos being in parallel between the same mains (*see* Fig. 1). The armatures of the alternators are arranged in parallel between a pair of primary mains, working, if need be, in step with each other, and the primary coils of the transformers are all arranged in parallel between the same primary mains. The secondary circuits of the transformers are arranged in parallel with the lamps between the same secondary mains. The exciting dynamos are shunt dynamos, and the field-magnets circuits of these dynamos are also all arranged in parallel, and take currents off the main circuit of the exciting dynamos, into which the armatures of the exciters are as well all joined in parallel. There is a variable resistance interposed in the circuit of all the fields of these exciters, by the variation of which the strength of the exciter field can be varied, and hence the electromotive force of the exciters. The field-magnet circuits of the alternators being all joined in parallel with each other and with the armatures of the exciters, it is obvious that the variation of this intercalated resistance can be made to change the strength of field of the alternators; and hence the electromotive force of these machines within certain limits. The transformer circuits are joined in parallel between the primary and secondary mains. From some point in the secondary distribution system, which may be called the electrical centre of the network, a pair of voltmeter wires can be brought back to the station; and by an arrangement presently to be described, the regulating resistance can be properly varied so as to keep the electric pressure at this electrical centre of distribution constant. Voltmeter wires, or *feeling wires*, may be brought back to the station from more than one point, and the pressure at any one of these points regulated as the demand for current requires. The variation of one resistance controlling the field of the exciters, therefore, is able to effect the regulation of the electric pressure in the secondary circuits over large areas of distribution.

§ 3. **Ganz Alternator.**—Proceeding, then, more particularly to describe the elements of the system, we take first the alternator, or alternating dynamo. The most recent type of Ganz machine, called the A type, is an alternator of that class in which the fixed or stationary electro-magnetic portion constitutes the armature, and the revolving portion the field-magnet. In Fig. 2 is shown a perspective view of the alternator, and in Fig. 3 face and end elevations. The field-magnet is a stellate electro-magnet, keyed on the steel shaft, which is the driving shaft. In the smaller sizes this shaft carries the usual pulley for belt or ropes keyed on outside the two massive bearings which are erected upon the bed-plate. A reference to Fig. 3 will also show how this stellate magnet

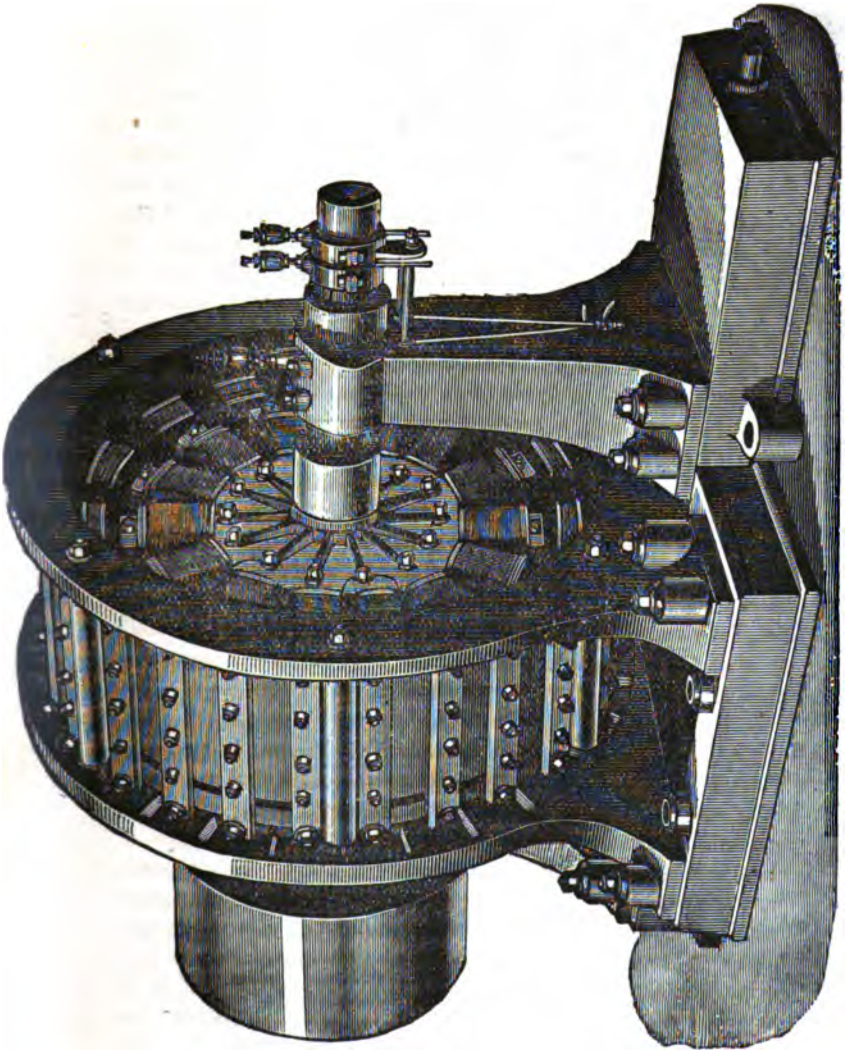
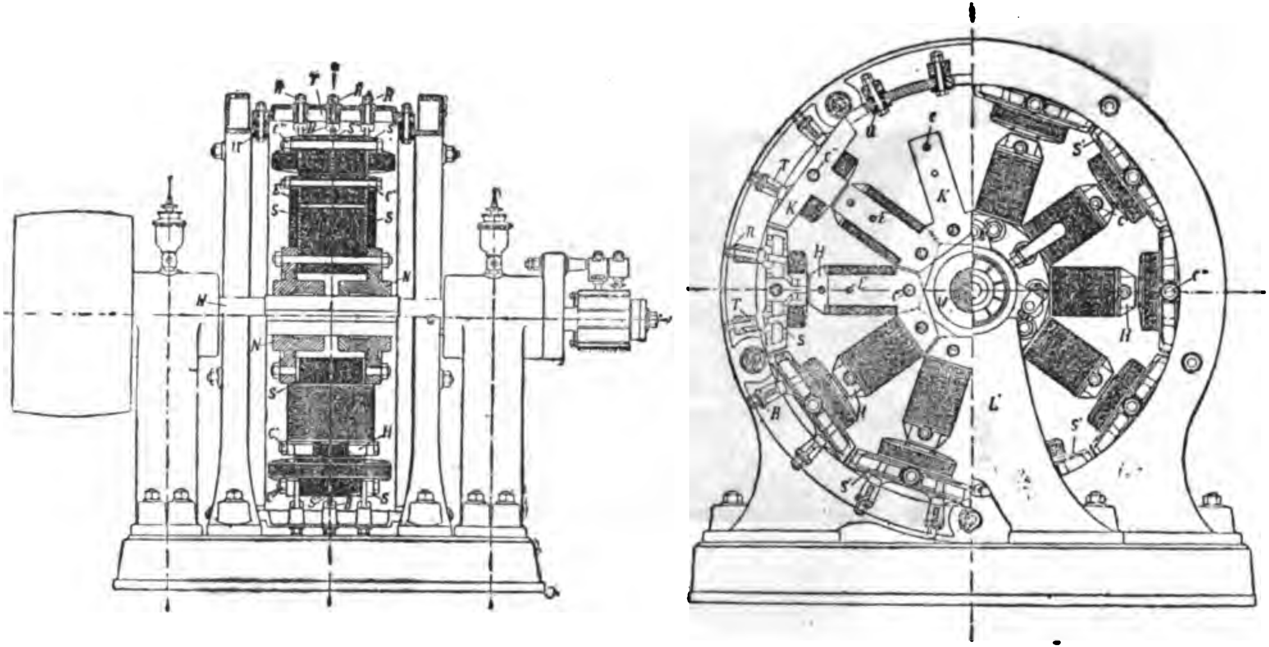


Fig. 2.—Ganz Alternator (Zipernowsky-Déri-Bláthy), 50 Kilowatt.



Figs. 3.—End and Face Elevations of Ganz Alternator.

is constructed. A number of V-shaped sheet-iron stampings (Fig. 4, *a*) are punched out and built up, with interposed laminæ of paper, into the cores, which are bolted in between two iron hubs or rings keyed into the shaft. These cores project like the stout spokes of a rimless wheel, and over them are slipped the magnet bobbins wound on split zinc frames. The bobbins are kept in position on the cores by a head or cap of gun-metal, which fits on the end of the laminated magnet core, and is firmly secured to it by a traversing bolt.

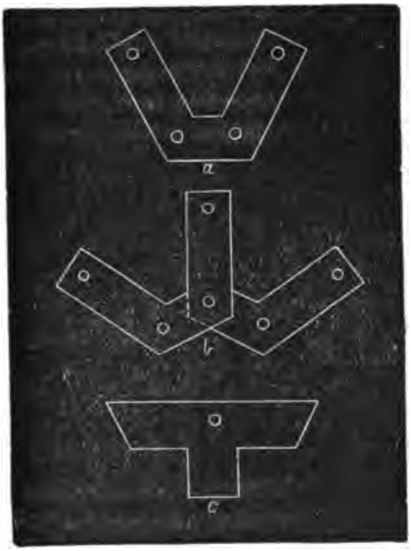


FIG. 4.—V and T-shaped Iron Stampings for building up Field-Magnet and Armature Cores.

The magnet poles are even in number, varying from 6 to 40 according to the size of the machine, and are alternately north and south poles. Surrounding this stellate magnet is the ring-shaped armature frame, formed of two massive iron rings kept apart by distance pieces and bolted together. This armature frame carries on its inner circumference the armature coils. These, like the field-magnets, consist of cores built up of sheet-iron stampings, T-shaped (Fig. 4, *c*), which are held together by bronze press-plates and by bolts. On to these cores are slipped the armature bobbins, which consist of vulcanized fibre frames, wound over with highly insulated wire. These bobbins are joined up in series in such manner that the currents induced in each are in the same direction, and generally one half of the armature coils is put in parallel with the other half, the individual coils in each half being joined in series. In like manner the several magnets of the field-magnet are divided into two sets, the magnet coils in each set being in series, and the two sets being joined up in parallel. The clearance between the polar faces of the field-magnets and the armature-magnets is very small. Each armature section is thus complete in itself, and can be removed or replaced in a few minutes. The armature sections are screwed to the distance-pieces of the main ring frame, but insulated from them by intervening insulating pieces. In building up the stellate electro-magnet core one layer of the V-shaped iron stampings is first arranged in the proper angular positions; another layer is then laid over them, with paper between, but so that the individual stampings of the second layer "break-joint" with those of the first, and the process continued until the proper thickness is obtained (*see* Fig. 4, *b*). Strong iron press-plates are then bolted up so as to compress all this mass of laminated iron into a star-shaped magnet. The bobbins having been put on the cores, the slightly projecting ends of the cores are fitted with bronze bobbin-holders, held on by a bolt which traverses the laminated pole, in order to prevent the bobbins from being thrown off when the magnet revolves.

In some of the larger sizes of machines the annular armature frame is made to slide along the bed-plate in guide slots by means of a screw. By this means the whole armature can be moved along laterally, so as to move it off the field-magnet, and enable this latter to be got at easily for repairs. The machines are made either to be auto-excited or separately excited. In the former case the excitation of the field-magnets is effected by a rectified alternating current. This current is supplied from the secondary circuit of a subsidiary transformer, whose primary is fed from the armature. The alternating current is rectified by means of a commutator keyed upon the shaft of the dynamo. This commutator is made in the following fashion:—On an insulating hub are arranged brass or copper cylindric sections, as many in number as the poles of the stellate field-magnets. These metal segments are insulated from each other, and separated by narrower metal sections insulated on both sides from the main sections. (*See* Fig. 5, in which the thick black lines represent tho insulating portions, mica). The narrower sections aro all connected together, and tho wider sections are also so connected that alternate large sections are in conducting contact.

In Fig. 6 we imagine the cylindrical surface of the commutator rolled out flat, the connections between the segments being represented by the firm and dotted lines. The brushes are represented diagrammatically in an oblique position. On opposite sides of the commutator there are two pairs of brushes, one brush at each side being a little in advance of its fellow.

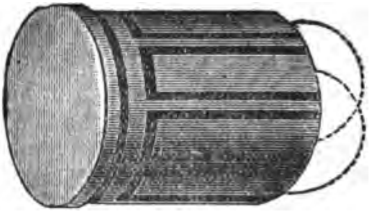


FIG. 5.—Diagram of Commutator for rectifying the Alternating Currents of a Ganz Alternator.

One set of the wide sectors, of which a member may be supposed to be in contact with one brush, is connected to the extremities of the field-magnet circuit; and the alternate sectors, one member of which is in contact with a brush on the opposite side of the commutator, are in connection with the other end of the field-magnet circuit. The alternating exciting current enters by one brush and passes through the field-magnet coils. As the electromotive force of the field transformer falls to zero and then reverses sign, so the sectors pass under the brushes, reversing the connection with the ends of the field-magnet circuit, and hence preserving the current through the field-magnets always in the same direction. The use of the second brush on each side in advance of its fellow, and also of the intermediate sectors on the commutator, is to prevent the spark at the instant when the brushes change sectors; and this is achieved by connecting the bushes on the same side of the commutator through a little resistance, one being a little in advance of the other, by an amount sufficient to place the one brush on the intermediate or neutral sector at the instant when its fellow steps off the "live" sector just behind it. At the instant, then, before the change of connection is made by the brushes leaving their respective sectors they are short-circuited by reason of the fact that their companion brushes are on the intermediate sectors, which are all in conducting connection. Hence the sparking, which would otherwise exist, due to the self-induction of the field-magnet circuit, is kept under, and the wear of the commutator greatly improved. This same device of a pair of brushes, one having a lead over the other to stop sparking, is employed in the Ganz alternating motor. (See *Electrician*, Vol. XXIV., 1890, p. 453.) The larger

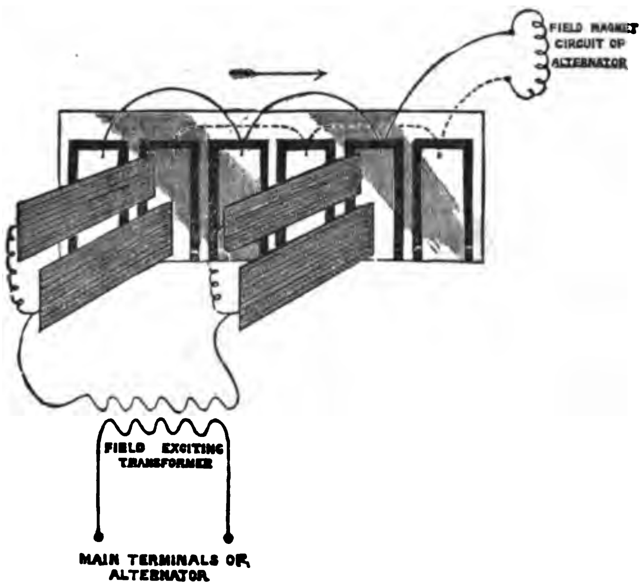

FIELD MAGNET CIRCUIT OF ALTERNATOR
FIELD EXCITING TRANSFORMER
MAIN TERMINALS OF ALTERNATOR

Fig. 6.—Diagram representing Action of the Commutator on Ganz Alternator.

sizes of the Ganz alternators are not self-exciting, but are excited by a continuous current from a separate exciting dynamo. In the smaller sizes (150 horse-power) of central-station alternators the magnetising current is conveyed into the alternator by means of copper contact rings and brushes pressing against them. In the larger sizes of central-station alternators (600 horse-power) the exciting current is conveyed into the alternator by a pair of flexible copper ropes, weighted at one end, and hanging over deeply-grooved brass pulleys insulated from, but carried on, the main shaft, and which are respectively the terminals of the field-magnet circuit.

In all these machines the magnets are so designed that at normal speed they produce a current having 5,000 reversals per minute, or about 83 per second, or a "frequency" of 42 per second—that is to say, the current has 42 complete periods per second.

The alternators are made in about eight sizes, varying in output from 10,000 to 380,000 watts, as shown in the following table :—

Ganz Alternators.—Type A.

Number......	1.	2.	3.	5.	6.	7.	8.
Nominal full load of dynamo in watts.......	10,000	20,000	30,000	50,000	80,000	160,000	380,000
E.M.F. at terminals in volts ...	1,000	2,000	2,000	2,000	2,000	2,000	2,000
Revolutions per minute	830	830	625	500	360	170	125
No. of poles on field-magnet ...	6	6	8	10	14	30	40
Weight of machine in tons.........	·7	1·1	1·7	3·4	6·1	11·0	23·0
Usual safe full load of dynamo in watts.......	9,650	19,300	28,950	48,250	77,200	154,400	366,700
Corresponding horse-power required to drive dynamo at usual full load.........	15·6	29·8	44·1	76	120	233	550

The values here given for output and absorbed power are taken from catalogue figures, and must not, therefore, be regarded as having the weight and accuracy which might be expected from careful independent tests. They are here given merely for the purposes of general comparison.

The exciting dynamos employed in connection with the larger sizes of machines are ordinary drum-armature shunt dynamos supplying current at about 100 volts. The field-magnets are of the well-known form of vertical single horse-shoe type, and are illustrated in Fig. 7, and call for no special remarks. In some cases of central-station work the exciters are direct-driven by coupled engines, and in other cases they are driven by a belt off the alternator shaft. The general practice is to cause two or three alternators to feed into a pair of mains which supply the field-magnet circuits of the alternators arranged in parallel across them. By this arrangement a breakdown of one exciter does not interrupt the maintenance of the fields of the alternators.

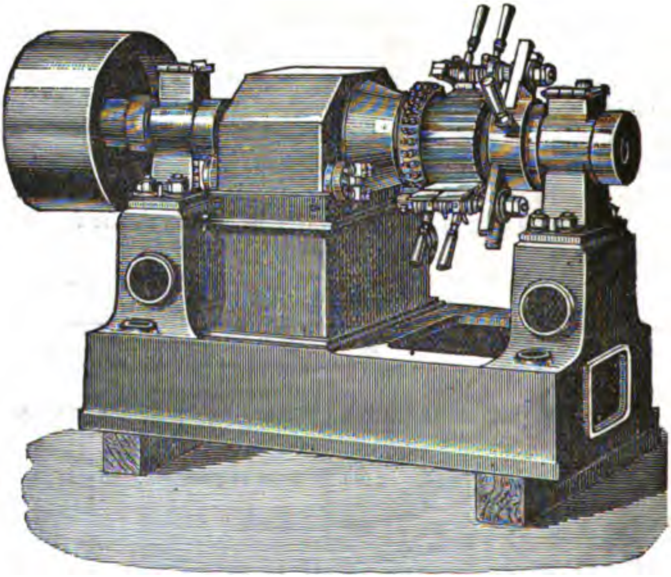


FIG. 7.—Continuous-Current Exciter Dynamo by Ganz.

§ 4. **Ganz Transformers.**—Proceeding next to the transformers, we may mention, in passing, the old life-buoy shaped transformer of Zipernowsky merely to point out that it is no longer used in practice. In that early form the primary and secondary coils were wound in circular coils, then laid together, and wound over with iron wire so that the whole arrangement looked like a stout circular ring. (*See* Fig. 8.) This form possessed a multiplicity of disadvantages. The heat generated in the coils themselves escaped with great difficulty. The magnetic resistance of the iron circuit was considerable, and any damage to the coils or insulators could only be repaired by taking the whole apparatus to pieces with great labour. Hence this type of shell transformer gave way to a more practically useful form. In the latest form, a series of sheet-iron discs like flat thin rings are stamped out; these are built up with interposed paper layers into a circular ring of laminated iron, having a square or rectangular cross section. These discs are held

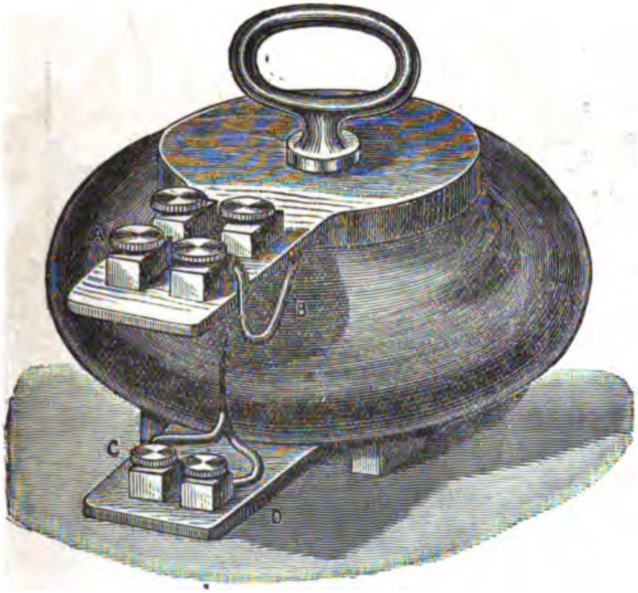
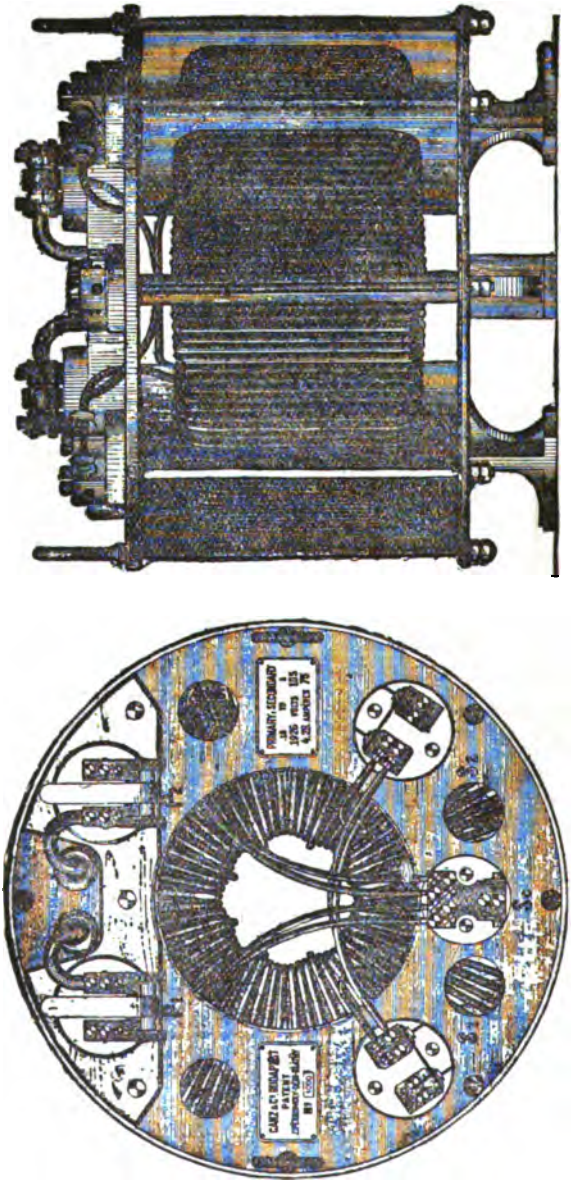


FIG. 8.—Old Form Zipernowsky Transformer (1885), not now used.



Figs. 9.—Gans Transformer (Zipernowsky-Déri-Bláthy), 1890.

together by radially placed clamping plates (*see* Figs. 9), which divide the ring core into partitions. The primary coils are then wound on the ring, covering it uniformly, and the secondary wire is put outside the primary. Iron discs top and bottom enclose the core and serve as supports for the terminals and fuses. The transformer roughly resembles a water-wheel, and can be rolled about easily when set on edge. On the top plate are fixed porcelain discs, which carry the primary and secondary fuses, which are short slips of fusible metal contained in glass tubes. The transformers are made in various sizes, to transform down generally to 105 and 52 volts, and each secondary circuit has three terminals by which 105 volts can be taken off for incandescence lamps, and 52 volts for arc lamps. The transformers are made in four sizes as follows:—

Ganz Transformers.

No.	Output in watts.	Weight in kilogrammes.	Commercial efficiency at full load as given by makers.
1.	1,875	70	92·5 per cent.
2.	3,750	110	94·5 „
3.	7,500	180	95·5 „
4.	15,000	290	96·8 „

The energy loss in magnetizing the iron is stated to be 5·5, 3·5, 2·5, and 1·5 per cent. respectively at full load in the No. 1, 2, 3, and 4 sizes, and the energy loss in the copper is put at 2 per cent. The primary coils are wound to receive current at 900, 1,800, 2,700, and 3,600 volts respectively in the four sizes, and to transform it down to 105 and 52 at the chief and intermediate terminals on the secondary circuit. The relation between commercial efficiency to the corresponding load on the secondary circuit in watts is given by the efficiency curve, as shown in Fig. 10.

This curve is given only on the authority of the manufacturers, but its general accuracy is probably sufficient for the purpose of reckoning the efficiency of the transformer at various loads. It has been confirmed fairly well by the independent tests made by the Frankfurt-am-Main Committee in 1890. This committee found that the latest pattern of Ganz transformer had at full load an efficiency of 95 to 96 per cent., at half-load 93 to 94, at quarter load 90, and at eighth load 80 per cent. efficiency. (*The Electrician*, Vol. XXIV., 1890, p. 439.) The experiments of M. A. A. Roiti,* to be again referred to later on, have also shown the efficiency at full load of a 3,800-watt Ganz transformer to be from 94 to 96 per cent.; but we defer to another chapter the full discussion of the methods by which these values have been arrived at. It is desirable, however, to make here a brief reference to some misleading conceptions which often surround the question of the efficiency of transformers in practical use. It has been frequently pointed out that there is a great difference between the *instantaneous efficiency* of a transformer at any moment, and the *mean efficiency* over any period such as 24 hours, during which it is loaded to very various degrees. The difference between these efficiencies may be considerable, the mean efficiency being often very much less than the maximum efficiency, and depending on the way in which the transformer is used. Given, however, a definite load curve—that is, a curve showing the load in watts on the secondary of the transformer at short intervals of time during the day, and an efficiency curve such as that in Fig. 10—the mean efficiency may be deduced as follows:—

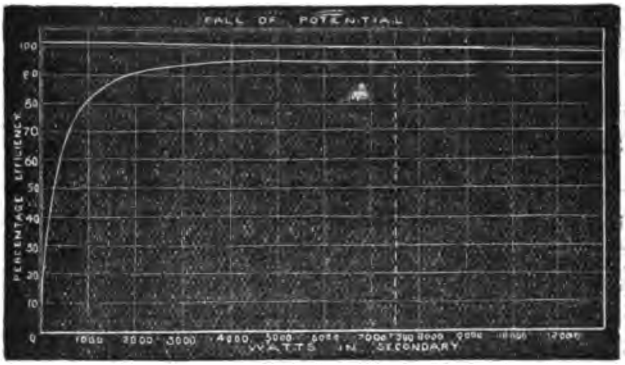


FIG. 10.—Efficiency Curve of Ganz Transformer, showing efficiency in per cents in terms of secondary load.

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[*] See *La Lumière Électrique*, March 15, 1890, Vol. XXXV., p. 525.

Let the ordinates of the firm-line curve in Fig. 11 represent the secondary load in watts, or the lamp-load on the transformer, at the various hours of the day. Increase each hourly ordinate of this curve in the ratio of 100 to the number denoting the efficiency of the transformer corresponding to the actual secondary load at that hour, which can be done from the efficiency curve giving the relation between efficiency and secondary load. Also if at any hours the secondary circuit is open and the secondary load therefore zero, ordinates must be set up at these points on the same scale proportional to, and representing, the power in watts absorbed by the transformer when the secondary circuit is thus open. Let the new higher ordinates define a curve shown by the dotted line. Then the ratio of the whole areas included respectively between the two curves, firm and dotted, the base line, and the bounding vertical lines, is a fraction which denotes the *mean efficiency* of the transformer during the twenty-four hours. If the load diagram varies from day to day, a further comparison of the daily mean efficiencies must be made to obtain the real average mean over any period of time, such as a year. It follows that a high efficiency at full load will not give a high mean efficiency unless the efficiency

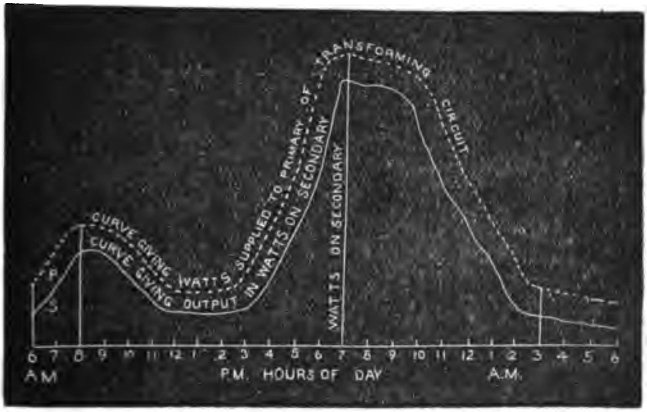

FIG. 11.—S (firm line) is a curve showing hourly variation of load on secondary circuit in watts. P (dotted line) is a curve showing corresponding variation of watts supplied to primary circuit.

curve of the transformer rises from zero very rapidly to its greatest ordinate. A transformer may have a very high efficiency at full load; but if it absorbs, when the secondary circuit is open, a sensible amount of power, and stands idle

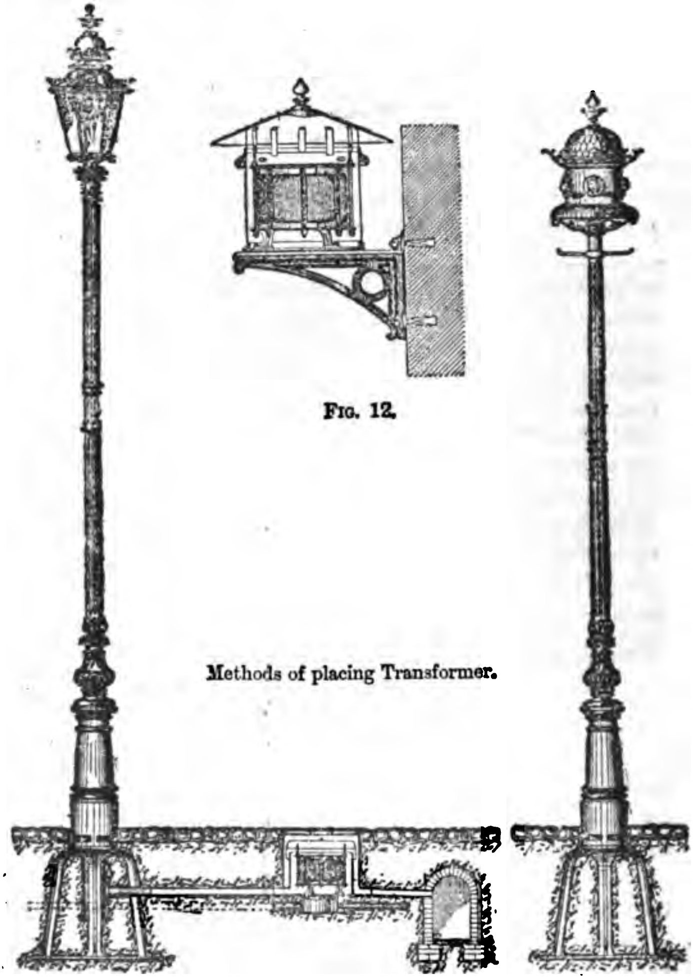

Fig. 12.

Methods of placing Transformer.

Fig. 14.

Fig. 13.

twenty hours out of twenty-four, its real commercial efficiency may be brought down easily to 50 or 60 per cent. or less. Further remarks on the bearing of this fact on the economy of working of transformer stations will be reserved until later. In central-station work done by this firm the 7·5 unit, or 7,500 watt transformer, is a very favourite size. The usual practice with Messrs. Ganz and Co. is to "bank" a number of transformers when a large secondary output is required, so arranging them that the primary circuits are all in parallel between the primary mains and the secondary circuits all in parallel with the secondary mains, and then to connect or disconnect transformers according as a larger or smaller output is required. In placing the transformers four methods are adopted. The transformer, when one only is required at a place, can be placed on a shelf enclosed in a weather-tight iron box (*see* Fig. 12), or it may be perched up on an iron pole like a dovecot, an ornamental form being given to the transformer case (*see* Fig. 13), or it may be buried in a watertight iron box (*see* Fig. 14), or some small fireproof dry room in the building to be supplied with current may be set apart as a transformer house, in which the transformers are arranged on porcelain insulators, on stone or wooden shelves, or resting on iron rails. This latter plan has much to recommend it in the facility it affords for getting at the transformer.

§ 5. **Pressure Regulating Devices.**—If an alternating-current dynamo is supplying current to a group of distant transformers through a cable laid between the localities, and if the load on the secondary circuits of the transformers varies, then the primary current flowing through the supply conductor will vary also. In order that the electric pressure at the terminals of the secondary circuits of the transformers may be kept constant in value, it is sufficient and necessary that the pressure between the primary terminals of the transformers be maintained at a constant value. Assuming that the primaries of the transformers are arranged in parallel between the primary conductors, it follows that whatever may be the variation in the primary current, the pressure between the terminals of the primaries of the transformers must remain the same. If the resistance of the cable is R ohms, and its self-induction negligible, and if V is the potential difference between the terminals of the alternator, and v is the potential difference between the terminals of the primary coils at the far end of the cable, then the current in the cable in amperes is approximately equal in magnitude to $\frac{V-v}{R}=C$. Hence, we have $v=V-CR$, and if v is to be kept constant, then it follows that as the strength of the primary current C varies, the potential difference at the terminals of the alternator must vary also, but so that the quantity $V-CR$ remains constant in value. The pressure at the terminals of the alternator must therefore not be maintained constant, but fluctuate with every change in the load on the transformers at the far end of the cable. It has already been pointed out that with the arrangements adopted by Messrs. Ganz and Co., this can be achieved by regulating the strength of the field-magnet current of the exciters; and MM. Zipernowsky, Déri, and Bláthy have devised an exceedingly ingenious method for regulating automatically the magnetising current of the exciters, in such a manner that the quantity $V-CR$ is kept constant for all values of the secondary loads. The arrangement adopted is called an automatic regulator, and is placed in the central station in some convenient position. It is diagrammatically represented in Fig. 15. A is the alternator, and L_1 L_2 the primary leads, or cable proceeding out from the station. In some convenient position in the station are placed two transformers, T_1 and T_2, called respectively the Shunt and the Series Transformers. The primary circuit of the transformer T_1 is placed in parallel across the leads L_1 L_2, and the primary of the transformer T_2 is placed in series in one of the leads L_2. The secondary circuit of T_2 is closed through a suitable resistance, R_2, and the secondary circuit of T_1 is closed through a solenoid, S, and resistances T, R_1 and R_2 as shown; the transformers T_1 and T_2 being so joined up that the secondary electromotive forces in T_1 and T_2 oppose one another as far as producing a current in the solenoid S is concerned. The potential difference between the secondary terminals c and d of T_1 is proportional to the potential difference V between the terminals of the alternator. The potential difference between the points a and b is, or can be, made nearly proportional to the magnitude of the primary current in L_2, and hence to the fall in volts along the cable or to C R. Hence the potential difference between c and b or between e and f can be made proportional to $V - CR$ or to v, the primary pressure at the primary terminals of the transformers. If a voltmeter Vl is joined up between e and f, this voltmeter can then be adjusted to read the same value as a voltmeter would do if placed across the secondary terminals of the transformers at the far end of the line. For the pressure at the secondary terminals is proportional to v, the pressure at the primary terminals of the distant transformers, and the indications of this voltmeter Vl are at every instant proportional to v.

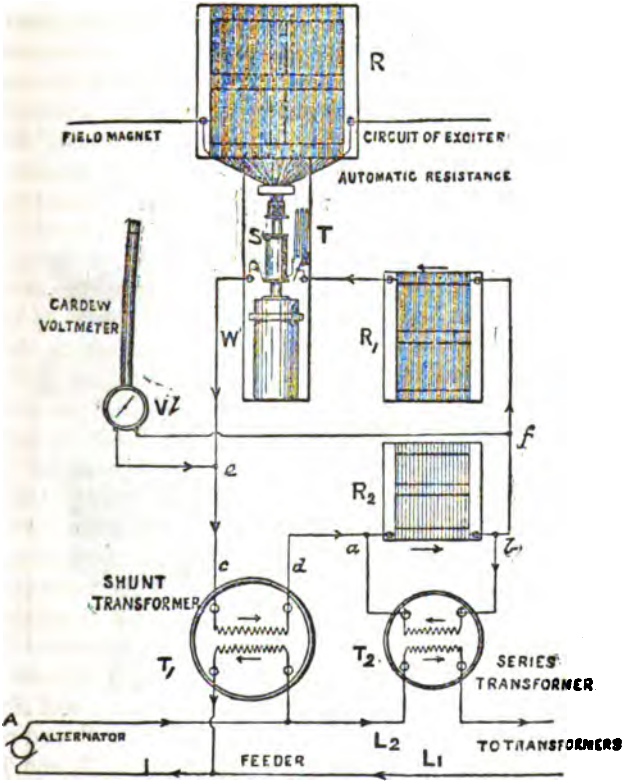

FIG. 15.—Arrangement of Pressure-Regulating Devices in Ganz System.

This voltmeter always indicates a pressure proportional to V - C R, which quantity it is necessary to keep constant.

The solenoid S is therefore traversed by a current, which is thus controlled in strength by the outgoing main current C and the terminal pressure V of the alternator. This solenoid is traversed by a tube or rod, partly of iron and partly of brass, the iron part so situated that a current in the solenoid tends to draw it up into the solenoid. This rod is held between

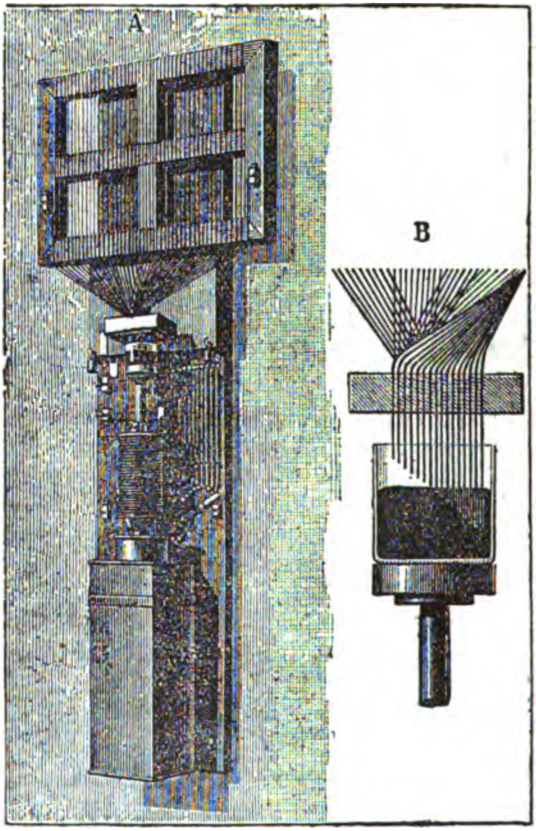

FIG. 16.—Mercury Cup, Float, and Solenoid in Ganz Pressure Regulator.

guide pulleys, so that it can move quite freely through the solenoid. It carries at its upper end a glass cup full of mercury, and at its lower end is a metal float, by means of which its weight is taken up when the float is immersed in a vessel of water. The diagram in Fig. 16 shows clearly the nature of these arrangements. Above the mercury cup is situated a resistance coil of iron wires, and the terminal wires of the sections into which this coil is divided are brought down into a group of iron wires bevelled off like pan-pipes, and so fixed in a block as to dip into the mercury in the cup (B, Fig. 16). It is easily seen, therefore, that as the mercury cup rises and falls it immerses a greater or fewer number of iron wires, and more or less of the coils on the resistance coil will be short-circuited by this immersion. This resistance coil is in the circuit of the field-magnet coils of the exciters; and hence as the mercury cup moves up or down in obedience to a greater or less attractive force of the solenoid upon the iron rod carrying that cup, so the field strength of the exciters is varied.

The connections are made so that if the current in the solenoid circuit, which is proportional in strength to $V - CR$, increases, the mercury cup is drawn down, and so intercalates resistance in the fields of the exciters and decreases the strength of the field of the alternators, and *vice versâ*. There is a small rheostat or resistance T in series with the solenoid S, by which large variations of the current in the solenoid can be made by hand, and in the same way large amounts of variation of the fields of exciters can be made by a hand-regulated resistance; and the automatic arrangements then can be set to keep the pressure at the far ends of the feeders constant within a given amount, so as to be independent of the changes of load. The above arrangement may seem at first rather complicated, but it does its work in practice very well, and its practical operation shows it to be one of the few devices of this kind which can be considered to be a thorough success.

The above described elements constitute the distinctive features of the transformer system elaborated by MM. Zipernowsky, Déri, and Bláthy, and we proceed to describe some of the central stations operated by the aid of these devices.

§ 6. **Central Station at Rome.***—In very fully describing this station in 1889, Prof. G. Forbes† called it the "finest example of an alternating-current central station;" and it well deserves this commendation. Since it was described by him it has been increased by the addition of two more large 600 horse-power engines and dynamos, and has now a complement of plant equivalent to a total output of 24,000 16 candle-power incandescence lamps. The electric lighting of Rome is carried out by the gas company, which has enlarged its operations and exists under the denomination of the Società Anglo-Romana per l'Illuminazione di Roma col Gas ed Altri Sistemi. The Directors of this Company were wise and far-seeing enough to recognise the necessity of dealing with the electric light either as an ally or as a rival, and in the spring of 1886 commenced operations for the supply from the gas works of the electric current by the Ganz alternating system. The gas works at Rome are in the Via dei Cerchi, near the Tiber, under the shadow of the Mount Palatine, and occupy a position in the region of old Rome, near the site of the ancient Circus Maximus; and in forming the foundations of portions of the heavy dynamo machinery some of the old arches of the Circus were exposed. The plan and elevation of the station are shown in Figs. 17 and 18, from which the general disposition of the machinery and buildings can be seen. The Central Station plant consists of two similar small alternators of 80,000 watt-power, giving a maximum current of 40 amperes at a pressure of 2,000 volts, which are coupled direct to engines of 125 horse-power, and of four large alternators of 320,000 watt-power, each giving a maximum current of 160 amperes at a pressure of 2,000 volts. The large dynamos are coupled direct to compound steam engines working up to 600 horse-power. The two smaller machines will be referred to as No. 1 and No. 2, and the four larger machines as No. 3, No. 4, No. 5, and No. 6, as

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* The author desires to acknowledge his indebtedness for the information on the details of this Central Station at Rome to Signor C. Pouchain, and also to Signor de Strens, Chief Engineer, who granted him every opportunity for examining the working of this interesting installation.

† "Some Electric Lighting Central Stations in Europe, and their Lessons," *Journal of Institution of Electrical Engineers*, Vol. XVIII., 1889, p. 172, and *The Electrician*, Vol. XXII., pp. 505, 528, 679, 716.

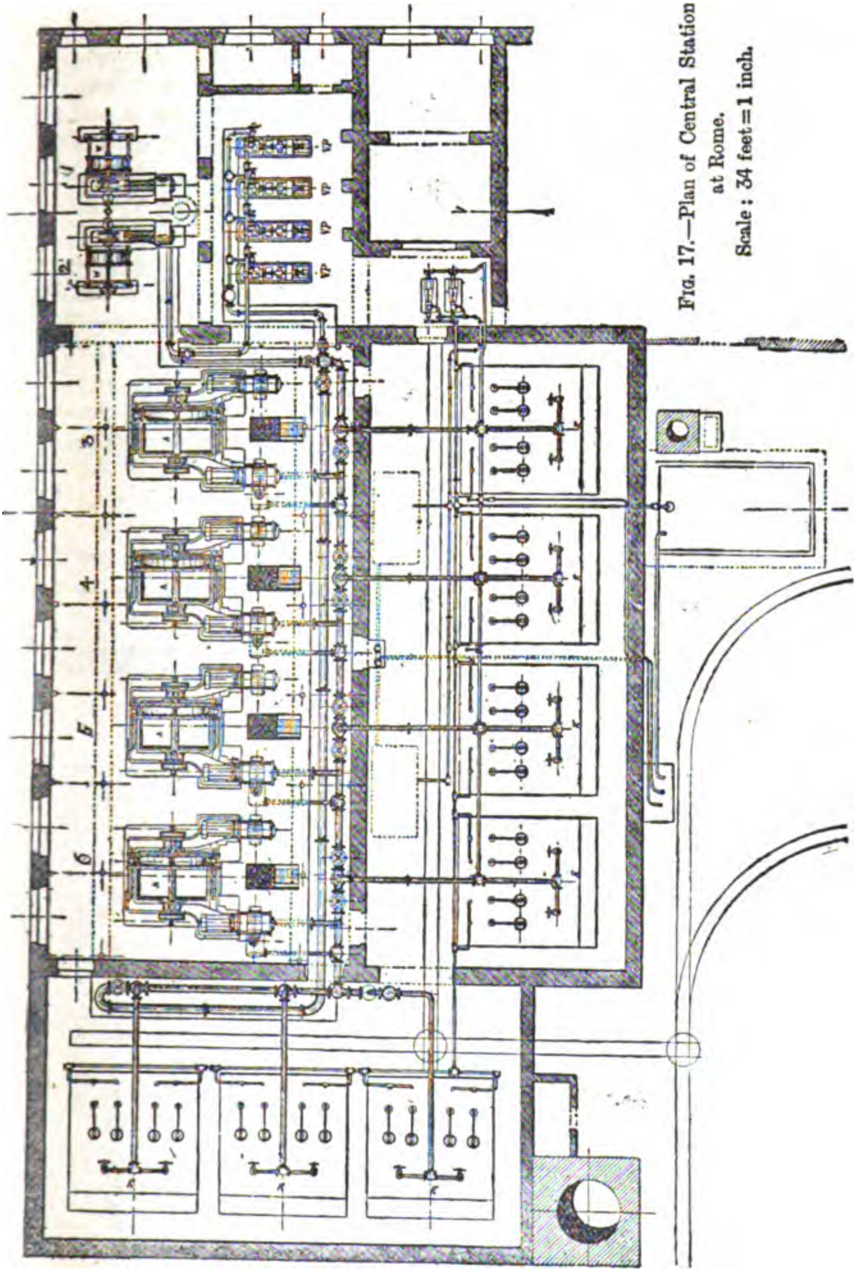

FIG. 17.—Plan of Central Station at Rome.

Scale: 34 feet=1 inch.

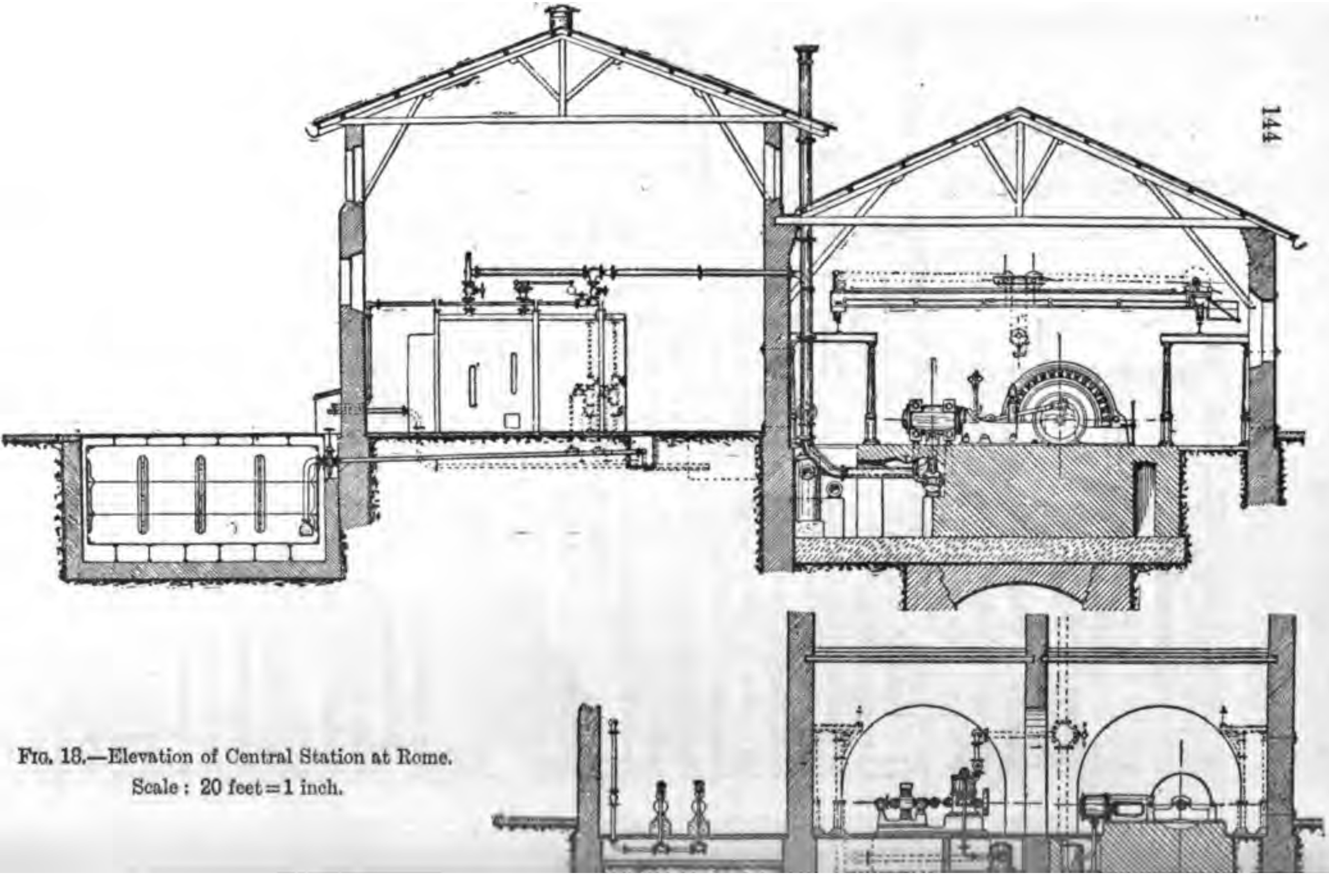

Fig. 18.—Elevation of Central Station at Rome.
Scale : 20 feet = 1 inch.

shown in the plan. The four larger machines are not all similar in details. No. 3 and No. 4 are sister machines, and also No. 5 and No. 6; but the last two have many improvements not present in the former two.

Commencing our description with the two smaller dynamos, placed in position and first used in the autumn of 1886, a general view of these machines is shown in Fig. 19. The engines are single-cylinder high-pressure engines by Gebrüder Sulzer, of Winterthur and Ludwigshafen. The speed is 250 revolutions per minute. These horizontal engines are built on a common bed-plate with the dynamo, and the revolving field-magnet of the dynamo forms the flywheel of the engine. The engines can be worked up to 150 horse-power. There are 20 coils in the fixed armature, and 20 poles in the stellate field-magnet, and in the armature all the coils are joined in series, each giving 100 volts, or 2,000 in all. In the field-magnets the coils are arranged in two series of 10 coils each, joined in parallel. The alternations are 5,000 per minute, or about 42 complete periods per second. These dynamos are auto-excited by a rectified alternating current and commutator, as above described, taking current from the secondary circuit of a field transformer, of which the primary coils are in connection with the armature of the alternator.

The larger dynamos No. 3 and No. 4 (placed in position and started in November, 1887) are separately-excited alternators, coupled direct to 500 horse-power compound engines by Van den Kirchoffe, of Ghent, these last having elaborate expansion valve gear of Corliss type, and also centrifugal governors of the usual kind; they have also starting gear. The dynamo is placed between the high-pressure and low-pressure cylinders, so that the field-magnet is slung on the centre of the steel main shaft. The ring-shaped armature frame has massive projections or lugs on either side, supported by, and traversing in, guide bars like the bed of a lathe, and it can be traversed laterally by a screw, so as to move it off from and expose the field-magnet revolving in the interior. The interior diameter of the armature ring frame is about nine feet and a-half, and the over-all diameter of the stellate field-magnet rather more than nine feet. In the dynamos No. 3 and No. 4 the field-magnets have solid cast-iron cores and wrought-iron polar caps or pro-

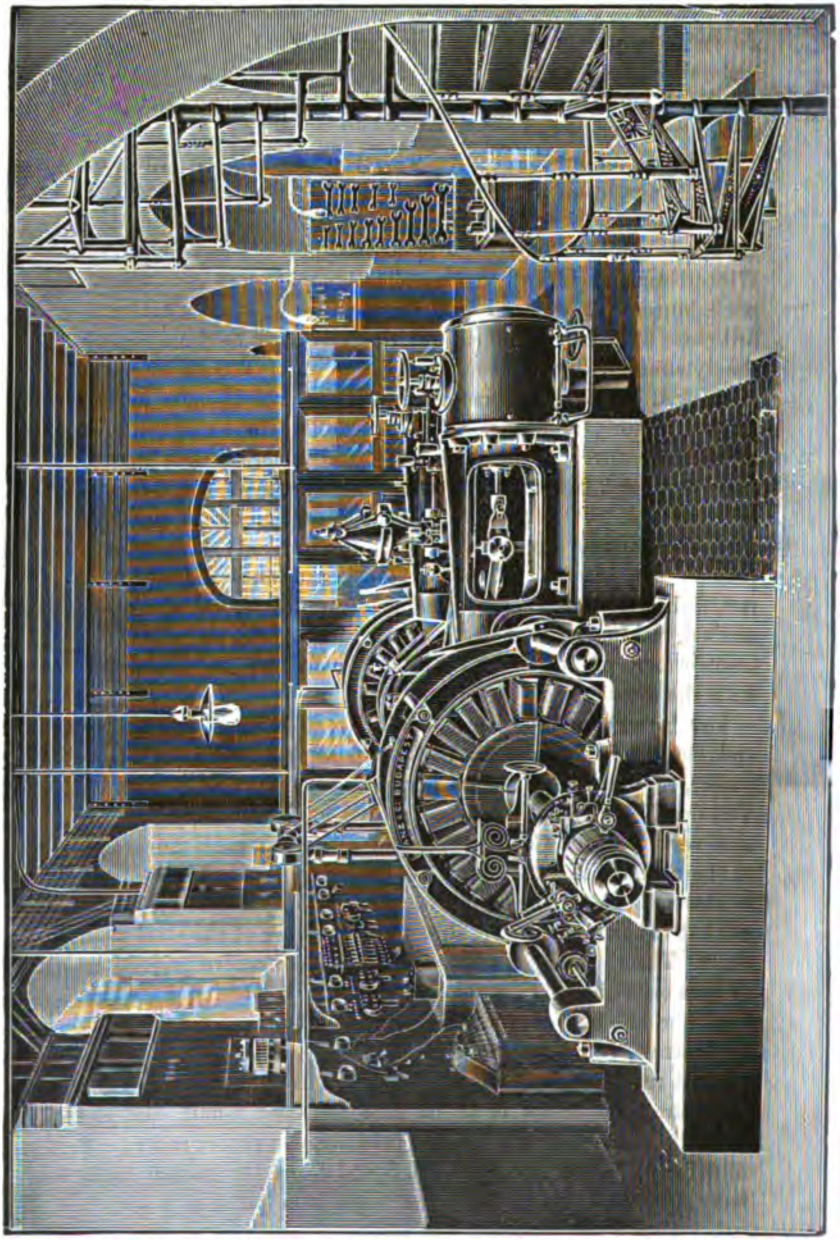

FIG. 19.—Small [illegible]ernators ([illegible] kilowatt) at Central Station, Rome.

jections; and these magnets, 40 in number, are placed round the periphery of an iron wheel keyed on the main shaft. The armature cores are built up of iron plates of thin sheet iron, with interposed paper, as described in a former section. The two smaller dynamos, No. 1 and No. 2, also have armatures built in this way with divided iron cores, and with solid cast-iron field-magnet cores having wrought iron polar expansions. In the armature of dynamos No. 3 and No. 4 there are 40 coils, each generating 50 volts, and the whole of them are joined in series. In the field-magnets the 40 coils are joined up so that there are two series of 20 coils in each, and the two series are joined in parallel. The engines make 125 revolutions per minute, producing, therefore, an alternating current of 5,000 alternations per minute, or 42 complete periods per second. The armature coils will carry safely 200 amperes, but their normal load is about 160. The copper wire on the armature and magnet coils is six millimetres in diameter, or about one quarter of an inch.

The last two large machines, No. 5 and No. 6, are generally very similar to No. 3 and No. 4. They are driven direct by compound 500 horse-power engines by the Erster Brünner Maschinen Fabrik of Austria; and in this case also the dynamo field-magnet is slung as a flywheel in between the high-pressure and low-pressure cylinders. In order to give space for the stellate magnet and annular armature frame, a pit is formed between the high-pressure and low-pressure part of the engine. These last engines have governors of the type employed in the well-known Armington and Sims engine, in which the lead of the single eccentric is shifted and controlled by the outward movement of two massive weights contained in the interior of a pulley-shaped governor wheel. This governor is, for convenience, placed on the outside end of the main shaft of the engine. The general appearance of these last two 500 horse-power dynamos is shown in Fig. 20. These engines have been found to do their work remarkably well, and to govern steadily. The general principle of this centrifugal governor is that of causing a change of speed of the engine to alter the lead of the slide valve and so cut off the steam at different periods of the stroke. This is accomplished by carrying the valve eccentric not directly on the shaft, but on a sleeve which can be shifted in position on

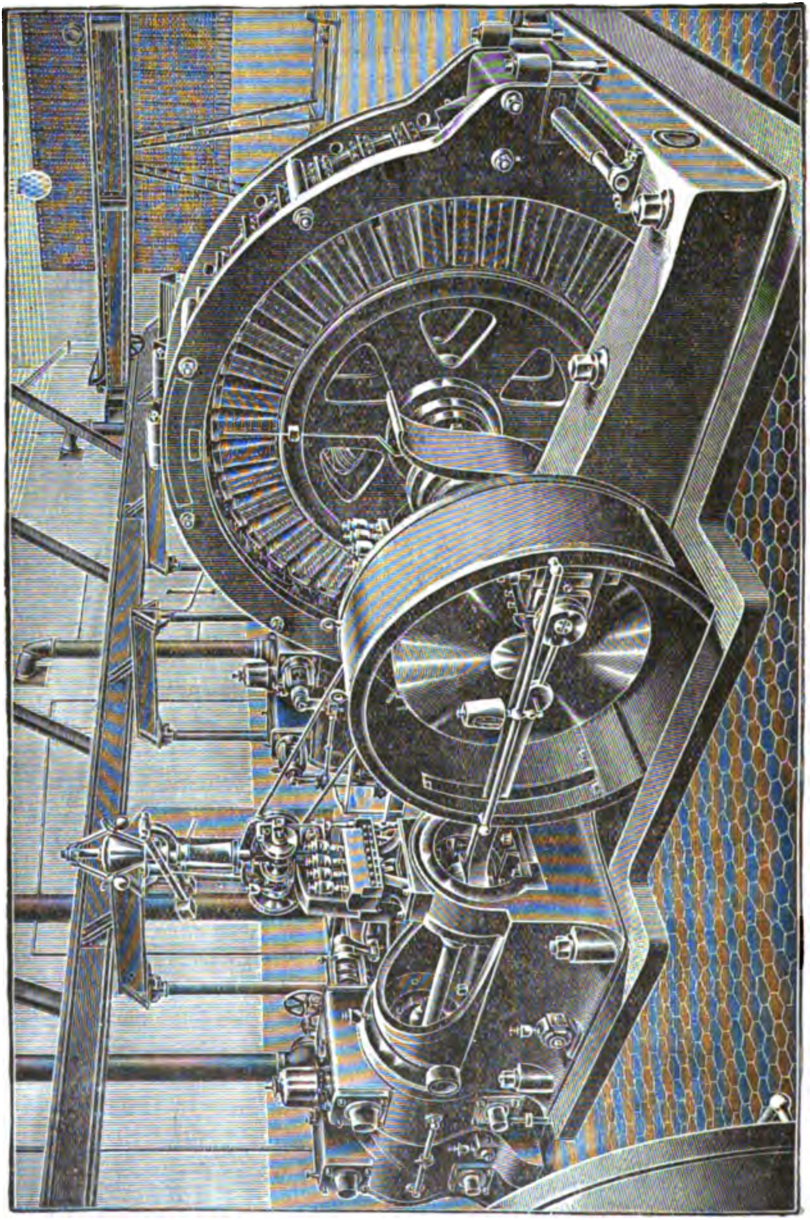

FIG. 20.—500 Horse-Power Compound Engine and Alternator in the Central Station, Rome.

the shaft, so as to change the angle of lead of this eccentric from a position in which the eccentric axis is nearly parallel to the direction of the crank to one in which it is nearly at right angles to it. According to the degree of this angle of lead so will the steam be cut off almost at the beginning of the stroke, or at a point rather less than three-quarters of the stroke. The work done by the steam pressure can therefore be varied within wide limits. The shift of the sleeve carrying the eccentric is effected by a set of jointed rods, which are moved by a pair of heavy weights carried on the end of levers, which are carried round with the shaft either in the flywheel or in a special governor wheel. The outward movement of these weights, caused by the centrifugal action, is resisted by powerful springs in the governor wheel, and any change of speed operates directly to shift the lead of the valve. In these last dynamos, No. 5 and No. 6, the cores of the field-magnets, as well as the armature cores, are built up of laminated iron, as described in § 3. The bobbins of the field-magnets are formed of rectangular split zinc frames, about 15in. high and 20in. wide. They are wound over with the insulated wire, but more wire is placed at the bottom of the frame than at the top, and the finished bobbins have a slight taper from about 8in. to 6½in. in end width. The armature bobbins are shallow rectangular bobbins, wound on vulcanised fibre frames about 19in. long and 10in. wide and 2in. deep. Each bobbin has on it about 30 turns of highly insulated copper wire, about 6 mm. or ¼in. in diameter. The armature coils when slipped on to the laminated iron cores are kept in position by bobbin holders of bronze, which form a kind of skeleton frame clamped on the end. The more massive electro-magnet bobbins are secured by a similar bobbin holder, and by a bolt fastening it which traverses the whole width of the laminated core. The terminals of the field-magnet circuit are led to two insulated brass pulleys deeply grooved, which are secured on the shaft. Over these are slung flexible copper stranded cables, one end of which carries a pendant weight, and the other end of which is in connection with the exciter circuit. This affords an excellent, and yet perfectly flexible, contact surface, for the exciter current to enter and leave the alternator field-magnets. The mechanical performance of these latest machines is very excellent; the dynamos run very smoothly and quietly, and give no trouble by any heating or insulation defects.

To excite these four large dynamos, there are three exciters driven direct by Westinghouse engines of 50 horse-power each, made by Alley and Maclellan. The exciting dynamos are by Ganz and Co., and are four-pole continuous-current machines, which, at a speed of 375 revolutions per minute, give a current of 150 amperes and pressure of 180 volts.

Since 75 amperes is a sufficient exciting current for each of the large dynamos, one exciter can excite two of the large dynamos, and hence there is always one exciter in reserve. At full load the power absorbed in exciting is said to be 3½ per cent. of total absorbed power. The steam is provided from a plant of fourteen Babcock and Wilcox tubular boilers, each of 160 nominal horse-power. Coke is burnt in the furnaces. Four steam pumps, in addition to the usual injectors, supply water to the boilers. The total boiler horse-power is 2,240. The steam pressure is 120lbs.

There are, therefore, in this station three pairs of machines, each pair consisting of two similar independently driven dynamos, but all yielding a current at the same electromotive force, and having the same frequency of alternation.

§ 7. **Cables at Rome.**—The current supplied by these machines is conveyed into three main conductors, often called the feeders. These consist of concentric cable made by Siemens and Halske, laid in wooden boxes filled in with cement and placed underground.* The construction of this conductor is well known. It consists of a core of stranded copper wires, insulated over with an insulation of jute impregnated with highly insulating material. Outside this is stranded the return conductor of copper wires enclosing the core, as in a tube; then more insulation, and finally a double twist of iron or steel tape and hemp protection over that. In Rome there are some 18 to 20 kilometres, or about 12 miles, of this main cable laid up to the present (1890). The cross section of each conductor is 220 square millimetres, or about one-third of a square inch. The main cables are laid in 100 metre lengths, with junction-boxes at this distance.

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* This plan of laying in cement has not been found to be satisfactory. In future it is probable the concentric cable will be laid in wooden troughing filled in with pitch or asphalt.

The three main cables all run together to the Piazza Venezia and then diverge in different directions, the most distant point reached being about 4½ kilometres, or three miles, from the station. The distance from the station to the point of divergence is about 1,600 metres, or one mile. The mode of making the junctions of the different lengths of the cables and of the branches has been most carefully thought out. The junctions are made in cast-iron boxes, in which these junctions are formed by copper straps, links, or clamps, and involve no soldering in making the joint in the street. The lids of the boxes are closed water-tight, and the box then pumped full of rosin oil. The diagrams in Figs. 21, 22, 23, and 24 show the various forms of junction box and mode of making the joint. Beyond the Piazza Venezia, the three mains give off branches in different directions, smaller concentric cable being used and the sub-mains run to the different groups of transformers. At the present date (1890) there are some 125 transformers installed, all being of the same uniform size of 7,500 watts, or 10 horse-power. These transformers are put in singly or in groups arranged in parallel in the various houses and public buildings, and feed about 12,000 100-volt incandescence lamps of 16 candle-power, 10 candle-power, and 32 candle-power, as well as some 300 Ganz alternating arc lamps of 8, 16, and 32 amperes, which are worked off the intermediate terminals of the trans-

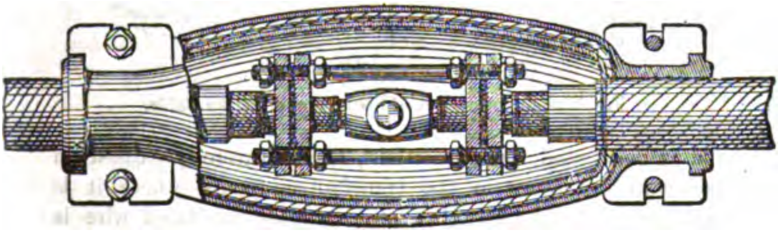


FIG. 21.—Simple Straight-Joint Coupling in Siemens and Halske Concentric Cable.

former. The transformers are placed in small fire-proof safes, boxes, or chambers, according to their number, and great pains are taken with the insulation of the primary wires. Bare copper rod is most used for connections, and is carefully carried on porcelain insulators in the transformer rooms, where it is possible to do so; in other places highly insulated wire is used. The transformers each take at full load about four amperes of primary current at 2,000 volts, and give out 75 amperes at 110 volts; the intermediate terminal enabling

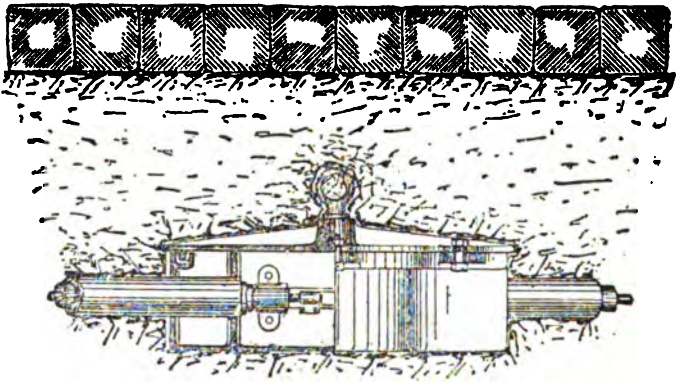


FIG. 22.—Junction-Box of Siemens and Halske Cable.

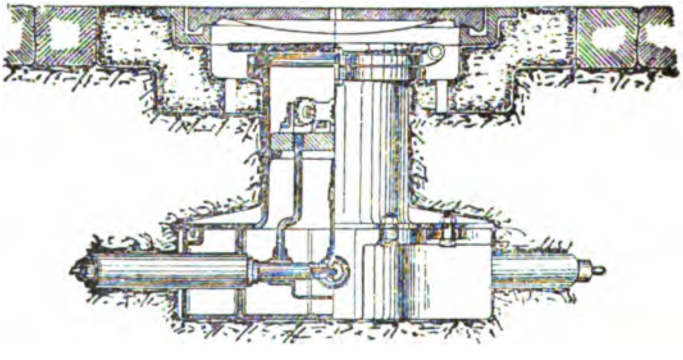


FIG. 23.—Surface-Box for Branch Junction, Siemens and Halske Cable.

arc lamps with resistances in series to be put on at 55 volts. A number of 10 horse-power transformers banked together is used in each of the large buildings lit. The lighting comprises not only street arc lighting, but lighting by arc and incandescent entirely of theatres, Senate and Chamber of Deputies, post, telegraph and public offices, besides shops and houses; the extreme variation of potential from point to point not being greater than 4 volts, and being regulated from the Central Station by keeping a standard pressure at one of three points in the network. The Argentina Theatre is lit by 1,800 incandescent lamps and 11 arc lamps, worked off 12 transformers, having their secondary circuits in parallel. Each arc lamp has a resistance in series with it which absorbs about 10 volts, and without

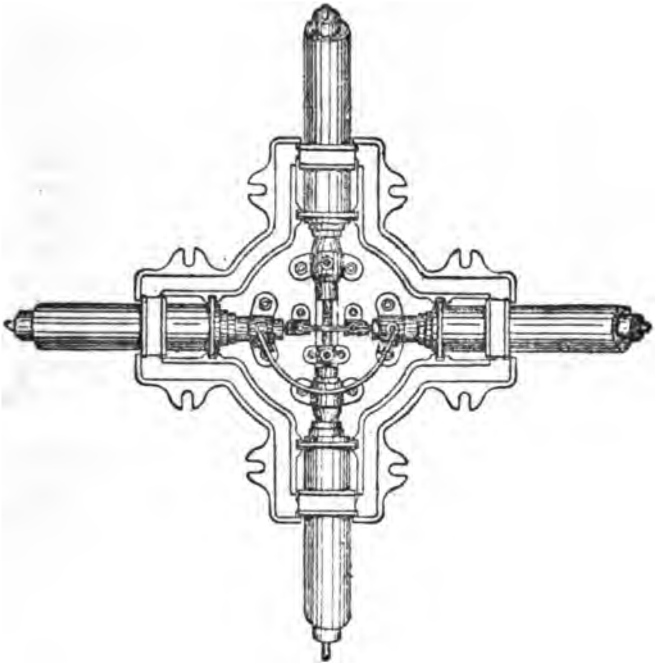


FIG. 24.—Cross Junction, Siemens and Halske Cable.

this resistance the arc lamps are not found to work steadily. With this resistance, however, they give a very excellent result; and the chief *cafés*, theatres, the railway station, and some of the larger shops, present a very fine exhibition of alternate-current lighting. It may be remarked in passing that a mere dead resistance should not be used for the purpose of steadying alternate-current arc lamps. A choking coil, preferably one having an air gap in it for reasons already given (*see* Vol. I., p. 267, *The Alternate-Current Transformer*), would afford the best means of securing the necessary steadiness.

This is not the proper place to enter into the vexed question of alternate *versus* continuous current arc lamps. The fact that at Rome 300 or more arc lamps are being employed indicates the necessity for making provision for arc lighting; and the economical question which has to be faced is whether the gain in simplicity of working by a uniformity of system is or is not counterbalanced by the disadvantages of intrinsic economy in the alternating parallel-worked arc as compared with series-worked arcs of equal mean candle-power, operated on separate circuits and by separate machines and, perhaps, by separate engines.

§ 8. **Change-over Switch** (Zipernowsky, Déri, Bláthy).—Although the dynamos in the Central Station at Rome are of different sizes, it has been found perfectly possible to work them in parallel together. As a regular rule this is not done, but each one of the three mains is supplied by a separate dynamo according as the load on it requires. As there are six dynamos and three main conductors the problem presented was to connect any one of the six dynamos to any one of the three mains, and to make any necessary change in the combination without extinguishing the lights. This has been solved by the construction of an exceedingly ingenious switch-board, which effects these changes with ease and certainty. The switch is an elaborate arrangement, and somewhat costly to construct. It will best be understood by the following diagrammatic sketches.

On a suitable framework (*see* Fig. 25) is carried a series of pairs of copper bars, D_1, D_2, D_3. D_1 and its fellow (not shown)

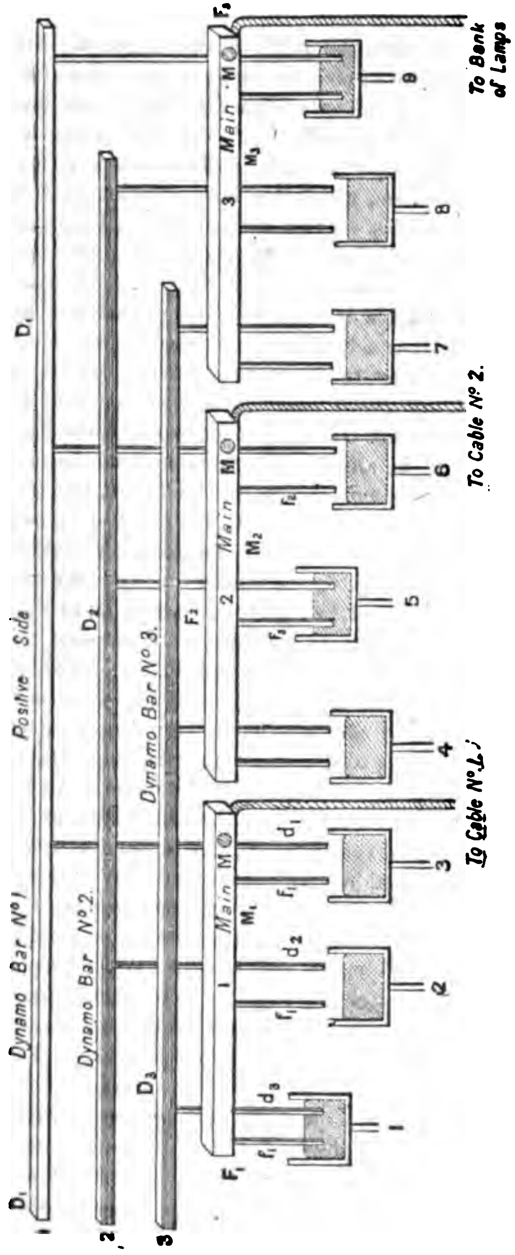


FIG. 25.—Diagram representing one side of Change-over Switch in Central Station, Rome.

are in connection with the poles of one dynamo. Similarly, D_2 and its fellow are in connection with the poles of a second dynamo, and so on. These bars are carried on insulators, and have pendant iron rods, d_1, d_2, d_3. There are a second series of pairs of copper bars, F_1 and its fellow (not shown), F_2, and F_3, and so on, which are in connection with the two leads of various cables. From these bars F_1, F_2, &c., are also pendant iron rods f_1, f_2, &c., and these are placed near the pendant rods, d_1, d_2, &c. Mercury cups, 1, 2, 3, &c., can be raised or lowered by a mechanism to be described, by which these pendant rods can be put in electrical connection, so that f_1 is joined to d_3, or to d_2, or to d_1, according as mercury cups 1, 2, or 3, are raised up. Hence, we see that the bars D_1, D_2, D_3, can be electrically joined to the bars F_1, F_2, and F_3, pair and pair, in any combination; and we must suppose that the fellow bars not shown in the figure, but which are the duplicate bars for the other side of the dynamo, are coupled similarly simultaneously. Suppose, for instance, that the mercury cups, 1, 5, 9, are raised up and the rest kept down; then D_3 is joined to F_1, D_2 to F_2, and D_1 to F_3. Thus, any dynamo can be put on any cable. Supposing that each dynamo is working on a cable, and it is desired to interexchange the positions of the dynamos, this can be done by raising and lowering mercury cups. For instance, let D_1 be joined to F_3, and D_3 to F_1, and let it be requisite to interchange the dynamos. What has to be done is to lower the mercury cups 1 and 9, and raise the mercury cups 3 and 7, and, if this is done very quickly, the dynamos and circuits will be interchanged without any sensible interruption of current. The mechanism for raising one group of mercury cups and lowering another, simultaneously, is carried below the frame which supports the copper bars. The mercury cups are carried in pairs (*see* Fig. 26) on a table, T, so that the dynamo and feeder pendant bars, F and D, from one side of the dynamo, dip in one cup, and the fellow bars, F′ and D′, belonging to the other side of the dynamo, dip in the other cup. This table, T, is carried on a pair of steel rods R, R′, which are crossed at the middle by a slotted distance piece, L, and the weight of the table and cups is balanced by a balance-weight below, not shown in the figure. The slotted bar L is traversed by the pin, P, of a crank, C. This crank is on a shaft, Q, working through a bearing, B, and the other end of the crank is supported by a pin, *p*, working in a bearing in the back of a slotted block, S, the slot in which is just wide enough to receive the square web of the crank C when the shaft Q is pushed forward by the handle H as far as it can go. When the shaft Q is pushed forward so that the crank arm C engages in the slot in the block S, it is easily seen that the crank can only be moved round with the mitre wheel, W; but that when withdrawn it has an independent motion of rotation. By turning the handle H when the crank is disengaged from the block S, the mercury cups can be raised or lowered through the distance of the "throw" of the crank, but if the crank is engaged in the block S, then the rise and fall of the table can be effected by a rotation of the wheel W. The crank can be obviously turned or inserted into the block S, either in the upper position or in the lower, and then a half-turn of the wheel W will either lower the cups or raise them.

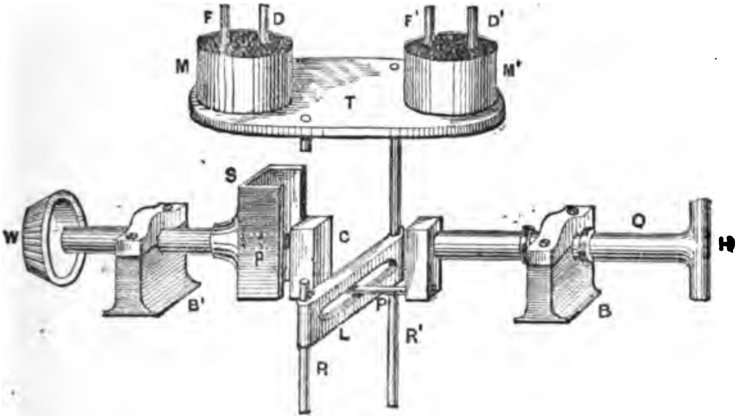


FIG. 26.—Diagram representing Cranks for Raising or Lowering Mercury Contact Cups in Change-over Switch at Rome.

Imagine a series of such cranks placed side by side (*see* Fig. 27) and each supporting its table and pair of mercury cups; and suppose the mitre wheels, W, attached to each shaft to engage in a series of mitre wheels, W′, all keyed on one long shaft. If a handle, K, is given half a turn, it will turn all the slotted blocks S half round, and it will raise, or lower, or not move, the table corresponding to each crank, according as that crank has been engaged previously in the slotted block in the upper or lower position, or withdrawn so as not to engage at all.

It is, therefore, obvious that by an appropriate position for each handle, any of the pairs of mercury cups can be caused to rise, or fall, or not to be moved, when the handle K is turned half round. Returning to Fig. 25, we can now see that a mechanism can be suitably arranged to effect simultaneously the electric connection or disconnection of any dynamo from any main, and that any possible combination can be instantaneously exchanged for any other.

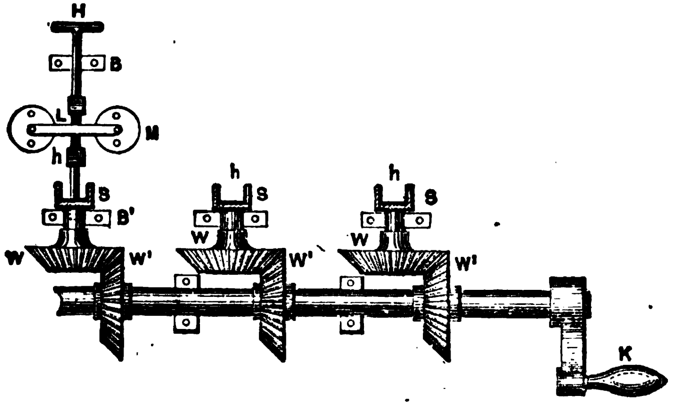


FIG. 27.—Diagram of Mitre-wheel Arrangement in Change-over Switch at Rome.

In the change-over switch at Rome there are four pairs of bars corresponding to the three mains, and to a bank of 3,600 lamps in the station which is used as an artificial load on which to run up each dynamo to speed.

If any main is being operated by any dynamo and it is desired to replace this dynamo by another, the incoming dynamo is first run up to the same amperes and volts as that of the circuit dynamo it is about to replace. The change-over switch is then brought into action to interchange the dynamos working on the circuit and that working on the artificial load; and so perfect is the operation of this switch that, when smartly worked, not the slightest wink can be seen on the circuit lamps. This switch is used to replace the small day dynamos by the bigger ones, at nightfall, and when required, or to effect any interchange necessary. It is, no doubt, an expensive switch-board to construct, but it does its work admirably.

§ 9. **Transformer Station at Leghorn (Livorno).**—At Leghorn there is a central station in the Via Costanza, on the same general plan as that at Rome, for distribution of electric energy by means of transformers. The plant was constructed by Ganz, and the machines and regulating apparatus are similar in general design to that described in the foregoing sections. A general view of the machine-room is given in Fig. 28. There are at present (1890) three combined engines and dynamos in position. The engines are direct-acting, high-pressure single-cylinder engines of 150 horse-power, fitted with centrifugal spring governors, the governor wheels forming also the pulley by means of which the exciters are driven. These engines are coupled direct to Ganz alternators of the A type, similar in design to those at Rome. The alternators furnish at maximum load a current of 40 amperes at 2,000 volts, and are therefore 80 kilowatt machines. The dynamos are driven at a speed of 250 revolutions per minute. The armatures have 20 fixed bobbins, and the revolving field-magnets 20 bobbins; hence the current has 5,000 alternations per minute, or 42 complete periods. The armature frame rests on a massive bed-plate, on which is also erected the engine; and the arrangement of slotted bed-plate and screw before described renders it possible to traverse the armature away from the field-magnet, and get at it for repairs. Both the field-magnet cores and the armature coil cores are built up of laminated iron plates. There are three such steam dynamos placed side by side; they take steam from a battery of three Babcock and Wilcox water-tube boilers, each of 150 horse-power size.

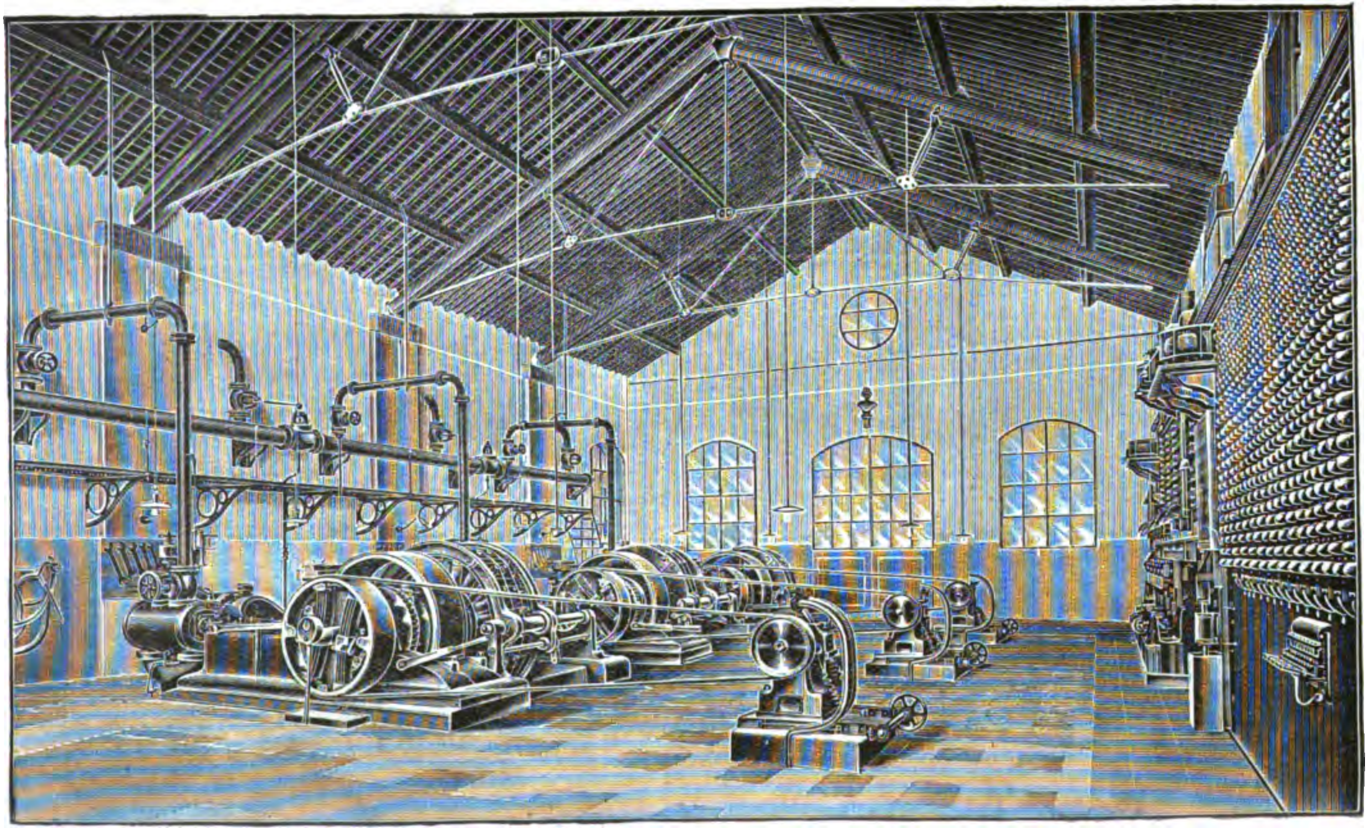


FIG. 28.—View of Central Station, Leghorn.

The exciters are driven off the governor wheel of each engine, and each furnish an exciting current of 25 amperes, at an E.M.F. of 100 volts.

The alternating current furnished by the dynamos is employed to feed about 2,000 incandescent lamps of 16 candle-power. From the station proceed two primary circuits, each consisting of a pair of insulated overhead copper conductors of 28 square millimetres in cross sectional area. The primary current supplies 17 transformers of 7·5 kilowatt size, four of 3·75 kilowatt size, and one of 1·875 kilowatt size, having their primary circuits arranged as usual in parallel between the primary mains. Although the station is not a large one, it is interesting from the fact that the alternators are worked in parallel on a single primary circuit as a regular thing. The two primary circuits start from a switchboard, which is exceedingly well arranged. The various connections on it are all made by highly insulated rubber-covered copper wire, carried on porcelain insulators, and the switches, cut-outs, &c., are all on porcelain bases, and have porcelain handles or covers. At one side of the switchboard (*see* Fig. 28) is a bank of 1,320 incandescent lamps. The usual voltmeters, amperemeters, and regulators, are conveniently placed. The automatic mercury cup resistance described in a previous section is also employed to maintain a constant potential at some point on the primary circuit, irrespective of the outgoing current. Each dynamo and engine can carry a load of about 1,200 16 candle-power lamps. When, therefore, the load on the external circuits does not exceed this, or equivalent to about a primary current of 30 amperes, the two separate primary currents are worked as one circuit on one machine. After midnight, when the load generally falls to less than 300 lamps, it is taken over by a small auto-excited alternator, worked by a separate small engine. When, however, the demand exceeds 1,000—1,100 lamps, two of the larger machines are worked in parallel on to the two primary circuits joined into one. The method by which this parallel working of the alternators is practically carried out is very simple. Let C_1 and C_2 (Fig. 29) be the two separate primary circuits, which may be supposed to be joined into one circuit by the plugs P_1 P_2. Let one alternator, A_2, be supposed to be working on this single circuit, and that

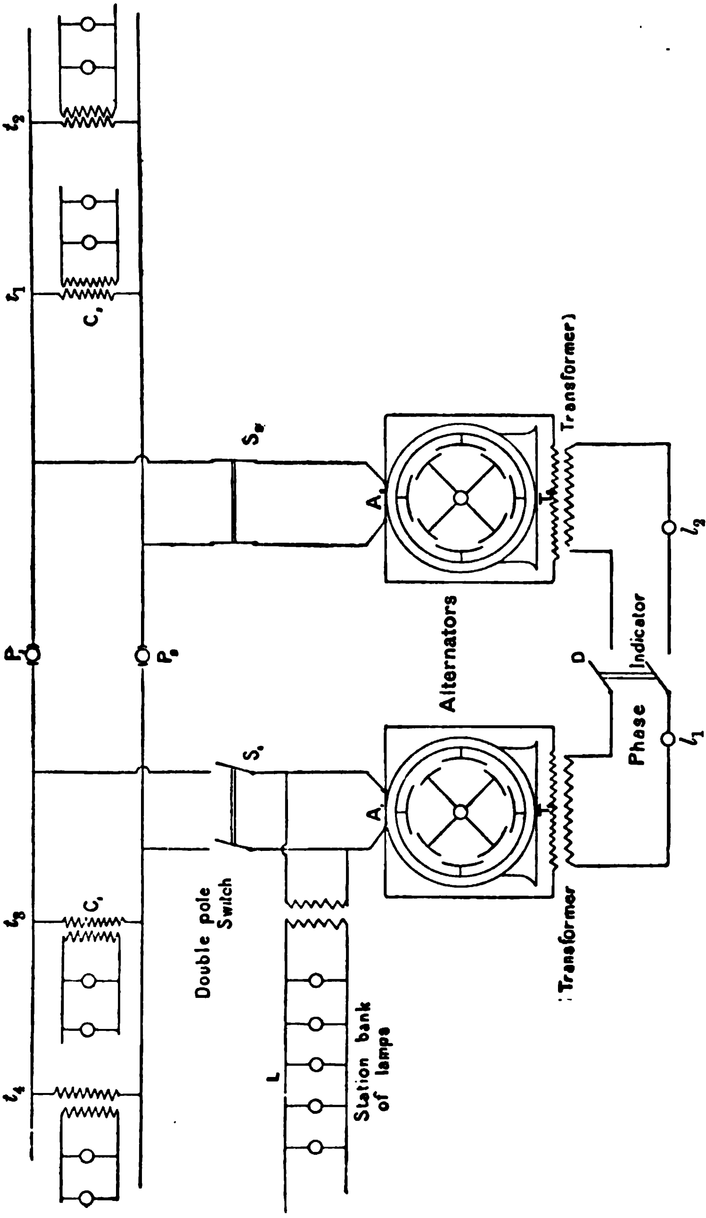


FIG. 29.—Diagram representing Phase-indicating Arrangement for Putting Alternators in Parallel on One United Circuit.

the time has come when a second alternator, A_1, has to be added in parallel with the first one to support the lamp load.

The first step is to run up the alternator A_1 to the proper speed and to set it to work on the station bank of lamps L and adjust its E.M.F. so that it has the same electromotive force and current output as the dynamo A_2 already on the circuit. From the poles of each alternator proceed leads to a pair of transformers, T_1, T_2, whose secondaries are joined in series through a couple of incandescent lamps, l_1, l_2. On closing the double pole switch D the transformers T_1 and T_2 work together on the pair of lamps; and according as the alternators A_1, A_2, are in similar or in opposite phase as regards electromotive force, so are the lamps l_1, l_2, extinguished or alight. The moment when the lamps l_1, l_2, are both out the two machines A_1, A_2, are in step, although on different circuits. As the machines pass out of step the lamps l_1, l_2, pulsate in brightness, producing luminous "beats" as the current pulses catch each other up. At the instant when the indicating lamps are not visibly luminous the double pole switch S_1 is closed. The dynamo A_2 is then in parallel with A_1 on the circuit C_1, C_2; the load of lamps on L is then removed little by little, and the two alternators A_1 and A_2 are finally left working on one circuit. Similar arrangements allow all three dynamos to be put in parallel. At Leghorn it is found to be very easy to throw in one, two, or three alternators in parallel as the lamp-load varies, and the machines keep each other in step perfectly when once they are put in parallel.

The station, as will be seen from the view in Fig. 28, is a one-story building, and consists of two rooms, one the boiler-house, and the other the dynamo-room. The station was opened in October, 1889, and has been in successful operation ever since. The station covers an area of about 45ft. by 100ft., and the present building can accommodate one more 150 horse-power engine, boiler, and dynamo, having, therefore, a capacity when full for three active dynamos and one reserve, or an effective output of 240 kilowatts, or 4,000 16 candle-power lamps in full use and for about 6,000 such lamps installed. This station is exceedingly well arranged; and as an example of alternators worked regularly in parallel is an interesting illustration of theory carried out into effective practice.

§ 10. **Transformers at Milan.**—Although the central station at Milan was designed originally on the lines of an Edison direct-current low-pressure station, it has been found essential to supplement the direct-current plant by an alternating transformer system to reach the outlying districts of the City. There are at the present time (1890) two combined engines and alternators by Ganz in the Milan central station, which machines are generally similar in arrangement, although slightly different in details to the steam dynamos at Leghorn. These alternators are of the 80 kilowatt size, driven direct by high-pressure engines at a speed of 250 revolutions, and generating a 40-ampere primary current at 2,000 volt pressure. There are no separate exciters, but the alternators take exciting current to the amount of about 28 amperes at 110 volts from the Edison low-pressure mains. These machines, of which one is a reserve on the other, feed, with the usual Ganz regulating arrangements, into one single underground conductor of the Siemens concentric pattern, which runs from the station in the Via St. Radegonda to the Dalverme and Fossati Theatres, about 1¼ miles, or 1,800 metres, from the station. In the Dalverme Theatre there is a bank of eleven transformers of the 7·5 kilowatt size, and in the Fossati Theatre two such transformers; these transformers feed between them about 1,300 incandescent lamps of 16 candle-power, 8 candle-power, and 10 candle-power. The cable carrying the primary current has a cross sectional area of 28 square millimetres in each member. The insulation after three years of working is very high, and is between 3,000 and 5,000 megohms per kilometre.

The transformers are of the latest pattern, as described in foregoing sections, and the arrangement for maintaining a constant potential at the supply end of the main is similar to that employed at Rome. The plant has been in perfectly satisfactory operation for three years, and will, no doubt, in time be greatly extended.

§ 11. **Other Transformer Stations by Ganz.**—The distribution of electrical energy by alternating-current transformers is making very considerable progress in Italy, under the system of Zipernowsky, Déri, and Bláthy. The following list gives the locality and approximate output (in 1890) of these stations in Italy :—

Station.	Motive power.	Full capacity in kilowatts.
Alanzo	Water	100
Bagni	„	15
Bassano	„	50
Cuneo	„	150
Palermo	„	40
Perdehohe	„	30
Terni	„	240
Trevisa	„	60
Taglicozzo	„	15
Leghorn	Steam	240
Milan	„	150
Rome	„	1,440
Syracuse	„	150
Turin	„	300
Venice	„	160

From the above table it will be seen that at the date of writing (1890) the output of all the stations taken together, which work an alternating system, is about 4,000 horse-power, or some 3,220 kilowatts, and will in the immediate present be very greatly extended in consequence of the advantages offered by this system in utilising water power. Already, as is well-known, a very large alternating plant is being arranged at Tivoli, near Rome, which is to be operated by water power, and to furnish current for lighting purposes in the City of Rome.

At Marienbad there is a transformer station also operated by similar plant, which was inaugurated in May, 1889. Street lighting is done by 36 alternate-current arc lamps, and by incandescence lamps, and about 1,800 glow lamps of 16 candle-power employed at private houses worked off a transformer system. The station is situated about a mile and a quarter from the centre of the town, and is a brick building, having an area of 600 square yards and divided into a boiler-house and engine-room. The dynamos are Ganz alternators of 50,000 watts output each. Four such dynamos are driven direct by Westinghouse engines made by Alley and Maclellan, in Glasgow. The exciters are driven by belts off the alternators. The alternators generate current at a pressure of 2,000 volts. The primary and secondary conductors are carried overhead on posts separated by about 35 yards, and the transformers are contained in weathertight receptacles also placed upon posts. Three alternators are usually coupled together in parallel during the heavy time of load, and one machine held as a reserve. The dynamos work perfectly well in parallel, and are put on or off the circuits by the same arrangements as those described for the Leghorn central station.

There is a small water-power transformer station at Valreas and Dieulefit, which is interesting as an example of transmission of power. Valreas (Vaucluse) and Dieulefit (Drôme) are electrically lit by means of power taken from a fall of water at Béconne, three miles from Dieulefit and nine miles from Valreas. At Béconne there are a couple of horizontal turbines, which yield each about 50 horse-power at 180 turns per minute. Each turbine drives a Ganz alternator of 24 kilowatts output and an exciter of three kilowatts output. The regulation of the turbines is effected by an hydraulic regulator by Bouvier, and the regulation of the primary electro-motive force at the consumption end of the line is effected by the use of a mercury cup rheostat as before described.

The primary current is conveyed by a bare overhead silicon-bronze wire, of 3·2 millimetres diameter (No. 10 B.W.G.), and a resistance of 11·8 ohms, to Dieulefit, and to Valreas by a similar wire of 6·6 millimetres in diameter (No. 3 B.W.G.) and 16·1 ohms resistance. The wires are carried on double-shed porcelain insulators. The transformers are held in iron cases carried on posts, and from them are distributed insulated secondary wires to the houses. The station, although very small, offers an interesting example of the conveyance and utilisation of water power by transformer plant.

In Paris, the Continental Edison Company carry out the lighting of the Palais de l'Élysée from their station situated about one mile and a quarter away, by means of Ganz alternators and transformers. Two alternators of 90 kilowatts and two of 24 kilowatts furnish current for 1,800 glow lamps in the Palace. The primary current is conveyed at a pressure of 2,000 volts by an underground concentric cable. The pressure is kept constant at the far end by the usual regulation of the exciting current, which is taken off from the direct-current machines in the same station. The four machines can be worked in parallel on to the single main, and the switchboard is arranged to permit this to be done.

§ 12. **Westinghouse Transformer System.** — In the last four years, beginning in 1886, the Westinghouse Electric Lighting Company has developed in the United States an immense industry in the manufacture and erection of alternating-current plant for distribution of electric energy by transformer systems. At the present date (1890) there have been established by this Corporation in America about 300 central stations, comprising a total of over 500,000 16-candle-power incandescent lamps operated by alternate-current transformers. The various portions of this system have been designed with great care, and the mechanical and electrical construction of all parts has been brought to a high level of perfection. The standard type of alternator is represented in Fig. 30 on next page. In this alternator the revolving portion constitutes the armature, and the stationary magnets the field. The field-magnet is composed of a series of radial magnetic poles projecting inwards from the interior of an iron ring-shaped frame. This frame is separable into two parts along a horizontal line. These magnets are arranged to have alternate polarity at the inner ends. The magnet cores are formed of solid or laminated wrought iron, bolted to the inner circumference of this cast-iron cylindrical frame. On these cores are slipped exciting coils wound on shells, which are held in position by bolts at the extremities. These field-magnet poles are excited by the current from a small continuous-current dynamo. The armature revolves in the cylindrical space in the centre of these radial magnetic poles. The armature core consists of a drum-shaped mass of laminated soft iron, built up of sheet-iron discs, compressed together and secured to the steel shaft. These discs are pierced with holes for ventilation. On the surface of this drum-core are laid flat coils of insulated wire wound on formers, and laid on side by side, so as to clothe the drum with one single layer of insulated wire coils. The ends of these flat coils of wire are bent over the flat ends of the drum, the whole set

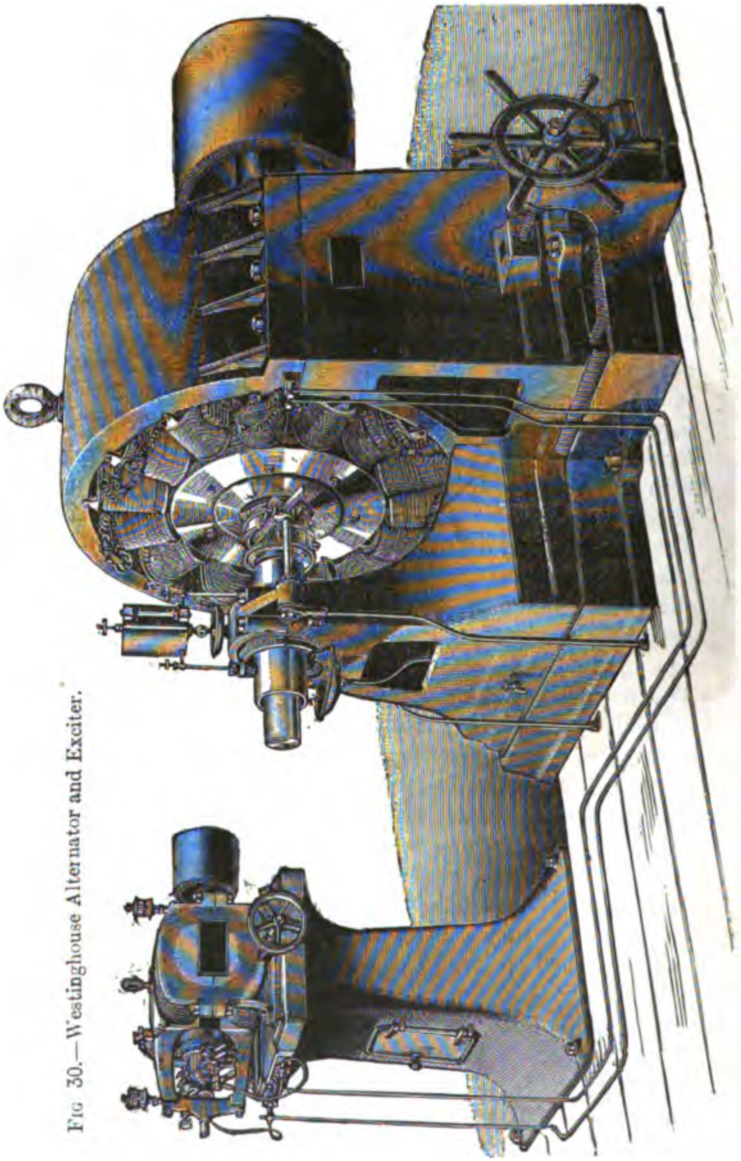


Fig. 30.—Westinghouse Alternator and Exciter.

being secured by brass wire-binding (*see* Fig. 31). The number of coils on the drum is equal to the number of radial magnetic field poles. The coils on each half of the drum surface are joined in series and the two series connected in parallel, the diametral terminal wires coming to collecting rings on the shaft. The armature can be easily removed for repairs by lifting the upper

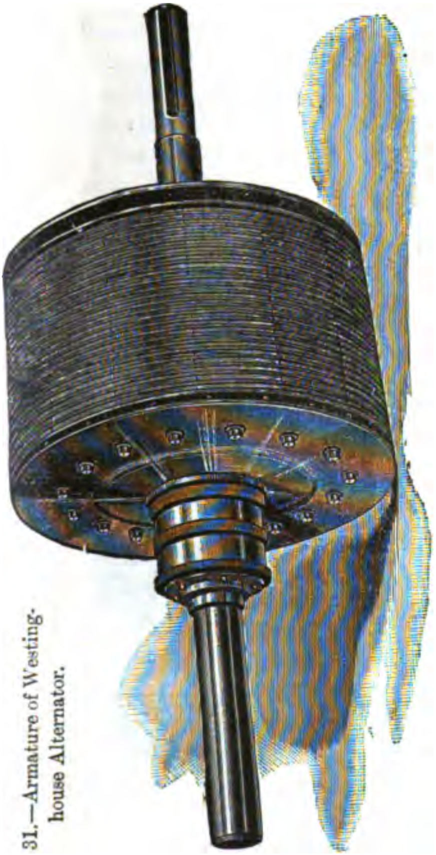
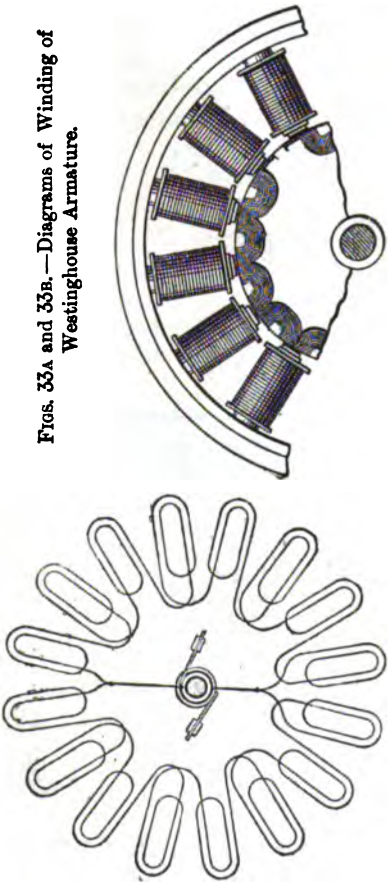


FIG. 31.—Armature of Westinghouse Alternator.



FIGS. 33A and 33B.—Diagrams of Winding of Westinghouse Armature.

half of the ring-shaped iron frame of the field, and then taking the armature and shaft out of its bearings. These bearings are ball-bearings, a section of which is shown in Fig. 32, and oil is fed from sight-feed oil cups to them, and working out into a drip pan, flows thence into a tank cast in the hollow base of the dynamo, from which it can be drawn off and re-used. The dynamo rests on a cast-iron base, and has the necessary belt-tightening arrangements.

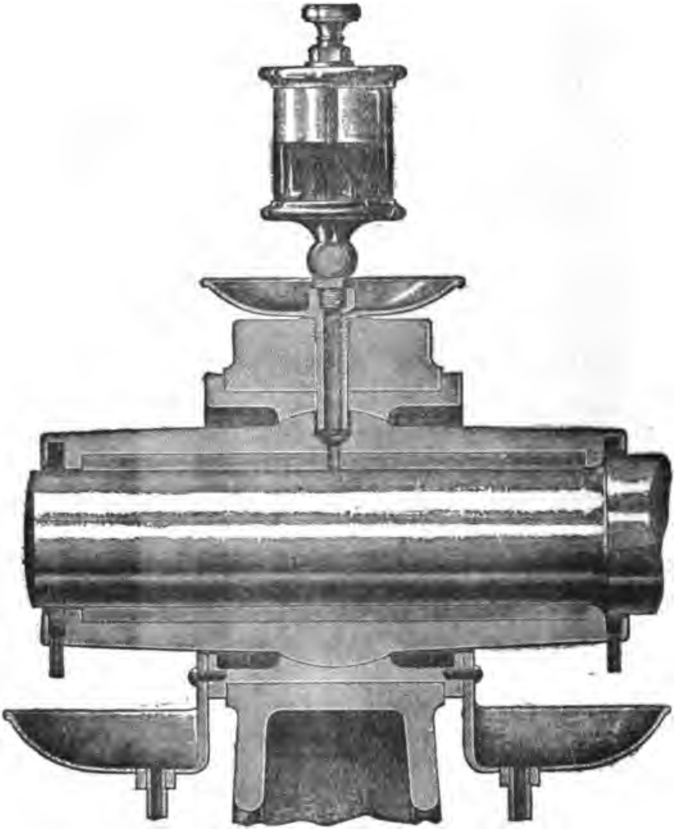


FIG. 32.—Ball Bearings of Westinghouse Alternator.

This dynamo is manufactured in five sizes—

No. 0, 500-lights, floor-space 4ft. 2in. × 5ft.
No. 1, 750-lights, floor-space 5ft. 2in. × 5ft. 6in.
No. 2, 1,500-lights, floor-space 7ft. 4in. × 7ft.
No. 3, 3,000-lights, floor-space 8ft. × 7ft. 6in.
No. 4, 5,000-lights, floor-space 11ft. × 8ft. 4in.

The capacity being reckoned in 16 candle-power 50-watt lamps.

In large stations, in place of having an exciter for each machine, it is usual to excite an entire battery of dynamos from one or two large exciters driven by separate engines.

The armatures of these dynamos are all wound to deliver current at 1,000 volts, and the five standard sizes furnish at full load 22, 33, 66, 132, and 235 amperes respectively. On the 750-light size the total weight of copper on the armature is 16lb., and as it is disposed in a single layer on the surface of the drum it is readily kept cool and well insulated.

The leading-out wires from the collectors are carried on lugs on the main-bearing caps. In the No. 3 size, which is a commonly adopted central-station size, there are 16 magnet poles projecting inwards from the frame. The exciting coils of these magnets are joined up in two series of eight coils, on the upper and lower halves of the ring frame respectively, and the two series of magnet coils are joined up in parallel. These magnets are excited by a continuous current of about 25 to 30 amperes, supplied at 100 volts. The speed of revolution is 1,000 per minute. The armature coils are joined up in a like manner. The number of complete periods per second, or the frequency of the alternation of the current is 130, or 8,000 per minute. Hence there are 16,000 alternations or reversals of current per minute.

The diagrams in Figs. 33A and 33B* (p. 169) will indicate the manner in which these armature coils are connected, and will show how the ends of the flat armature coils are turned over the flat end of the drum core to get them out of the way. The centre of the flat coil is occupied by a wooden lathe or core, and a narrow wood slip is inserted between adjacent coils. The whole armature when clothed with coils is wound round with turns of brass wire. The clearance space between the surface of the wire and the end surface of the magnet poles is very small. Hence the wire moves in a very strong field. In

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* These diagrams are from the British Specification, No. 9,726, of 1887. *See also* Brit. Spec., No. 9,725, of 1887.

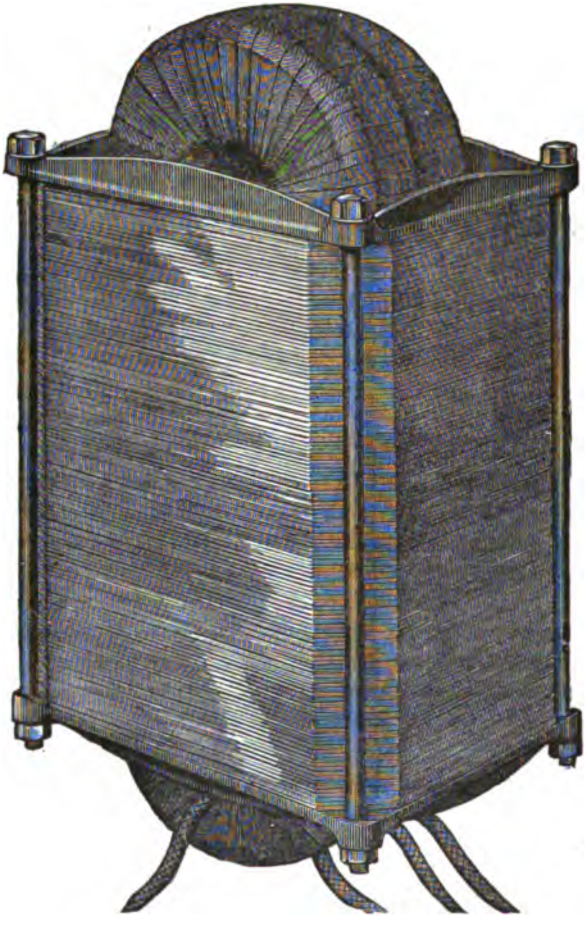
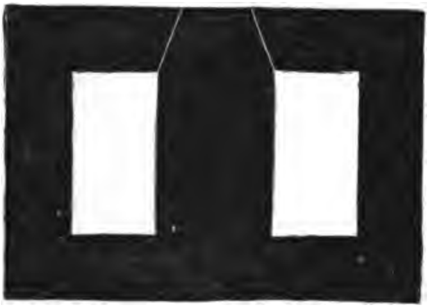
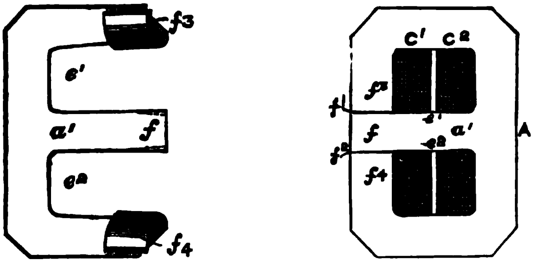


FIG. 34.—Westinghouse Transformer.

operating a battery of central-station dynamos, the whole of the field circuits of the alternators are joined in parallel with the armature circuits of one or more exciting dynamos operated by independent engines, the field-circuit of each alternator being controlled by a double-pole switch on the switchboard.

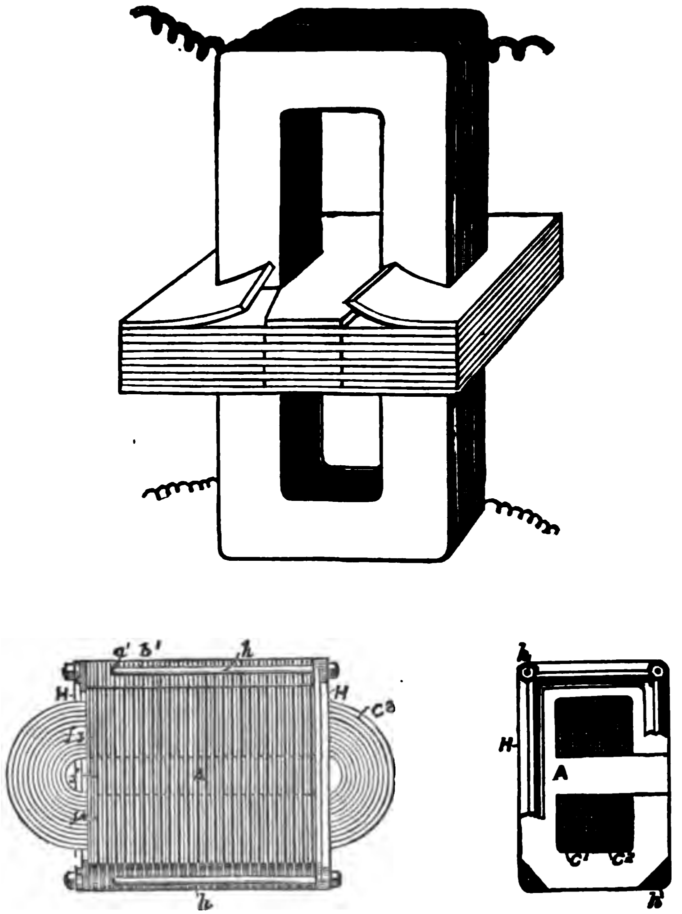
§ 13. **Westinghouse Transformers.**—The transformers or converters employed are illustrated in Fig. 34. The iron cores of the transformer consist of a pile of sheet-iron stampings,





Figs. 35.—Sheet Iron Stamping of Westinghouse Transformer.

which are built up to encase the primary and secondary coils. The sheet-iron stampings are shown in Figs. 35. The cross-pieces are bent back when the rectangle is slipped over the coils, and re-bent back into place, so as to enclose the coils within the iron. Each of these coils is composed of double covered wire, coated with an insulating compound, each layer of wire is insulated from its neighbour by additional insulation, and the completed coil covered with three separate and distinct coverings of insulating cloth. The contact between the primary and secondary coil is prevented by



FIGS. 36.

distance-pieces of insulating materials. The iron stampings being then piled up in and around the two coils (*see* Figs. 36), the whole is compressed by end-plates and tie-rods. The completed converter is enclosed in a cast-iron box, the two halves of which are bolted together with a waterproof joint (*see* Figs. 37 and 38). The ends of the primary and secondary coils are

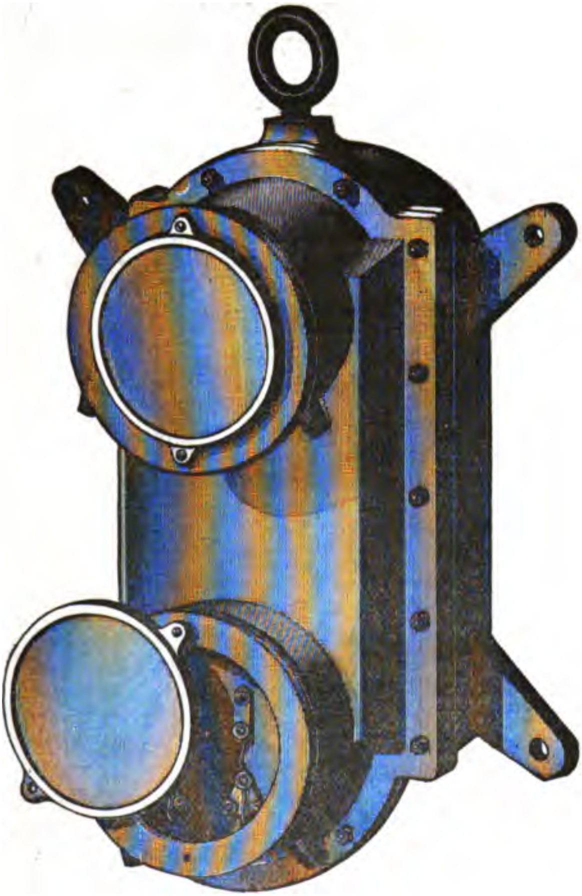


FIG. 37.—Westinghouse Transformer in Iron Case.

brought out to face-plates under swing lids. There are the usual primary and secondary fuses, these being covered in with glass plates. The converter case has a ring and lugs by which it is attached to walls of buildings or to posts. A very usual practice is to affix the converter to the cross-arm of the post carrying the primary wires or to the walls of a building (*see* Figs. 39A and 39B).

The converters are manufactured in four sizes for 500, 1,000, 1,500, and 2,000 watts output, or for 10, 20, 30, 40, 50-volt

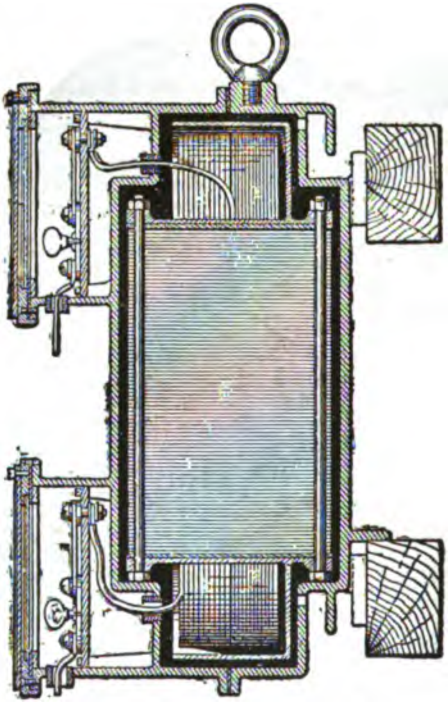


FIG. 38.—Section of Westinghouse Transformer in Case.

16 candle-power lamps. It is generally the custom to employ the converters singly on separate secondary circuits, and not to bank them with secondaries in parallel on the same circuit, as it is considered that if the primary fuse of one converter "blows," the additional load thrown on the other converters is apt to break down the whole set. The transformer generally used lowers

pressure from 1,000 volts to 50 volts. Although the converters are very light, and have a smaller quantity of iron in the cores than might be considered desirable, they appear to be efficient in performance. Comparative tests made by the calorimeter method at the Electrical Testing Bureau of the Johns Hopkins University, U.S.A., in 1889, gave results as follows for the electrical efficiencies of these transformers at various loads:—

Efficiency of Westinghouse Converters.

Capacity of transformer in 50-volt 16 candle-power lamps.	Power in watts supplied to primary circuit.	Output in watts on secondary circuit.	Watts lost.	Efficiency, in per cent.
	Full Load.			
10 lamps	585·3	504·0	81·3	85·9
20 „	1109·3	994·3	115·0	89·6
30 „	1529·0	1395·0	134·0	91·2
40 „	2151·0	2010·0	141·0	93·4
	Half Load.			
10 „	334·0	257·0	77·0	76·9
20 „	660·5	552·1	108·5	83·6
30 „	883·0	751·0	132·0	85·05
40 „	1243·4	1120·0	123·4	90·08

Prof. G. Forbes, employing the same calorimeter method on a 30-light transformer, obtained an efficiency of 95 per cent. at half-load. The calorimeter method is, however, one somewhat difficult to carry out with accuracy, and such discrepancies in results are not unlikely to occur even between careful observers. Tests made at the Institute of Technology, Massachusetts, employing the calorimeter, and using a 20-light converter, gave an efficiency at full load of 93 per cent.* In this case the alternations were 14,530 per minute. Probably the most complete tests on the efficiency of these transformers are those of Dr. Louis Duncan and Mr. W. F. C. Hasson, made in 1890 at the testing laboratory of the Johns Hopkins University, on a 750-light Westinghouse plant.* The dynamo was driven through a Tatham dynamometer by an Armington and Sims engine. Engine, dynamo, and dynamometer, were bolted down to heavy timbers, and the current conveyed to a bank of transformers of the 40-light size. These transformers supplied incandescent lamps. The efficiency of these converters was separately determined by a calorimeter method, by placing them in a metal box, with double walls, between which water was allowed to flow. The

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* *Electrical World*, Vol. XV., January 18, 1890, p. 46

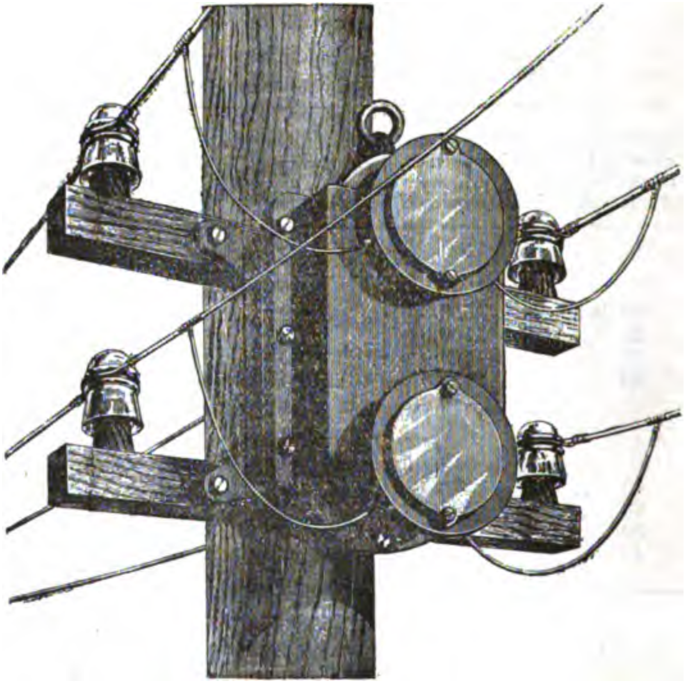

Fig. 39a.—Westinghouse Transformer affixed to cross-arm of post.

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* *Electrician*, Vol. XXIV., p. 593, 1890.

temperatures of the water at exit and entrance were observed, as well as the weight of water which passed through; at the same time the current and potential difference in the secondary circuit of the converter was measured. A series of corrections had to be applied for radiation. A 40-light and a 20-light converter were tested, with results as given on the next page.

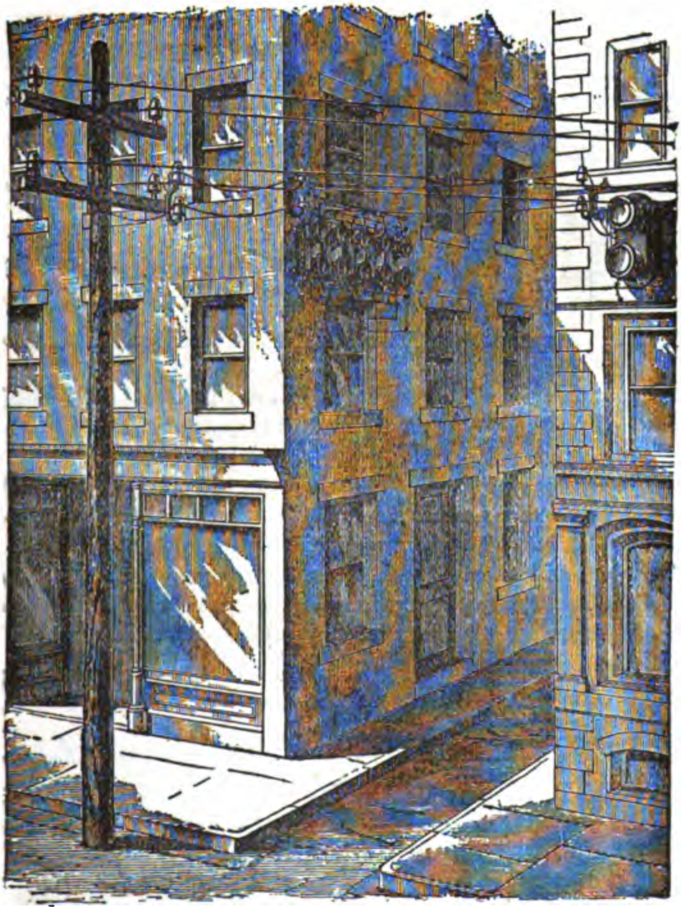

FIG. 39B.—Westinghouse Transformers affixed to exterior of buildings.

Efficiency of a Westinghouse Converter, 40-Light.

No. of lamps on.	Volts of lamps.	Watts in secondary circuit.	Loss in watts in transformer.	Loss in iron in watts.	Efficiency, in per cent.
40	50·0	2,000	109	...	94·8
0	50·9	0	84	84	...

Efficiency of a Westinghouse Converter, 20-Light.

20	48·8	952	106·0	95·2	90·0
15	52·2	817	114·8	108·9	87·6
10	50·3	506	101·7	99·2	83·3
5	51·44	264	109·4	108·7	70·7
0	52·3	0	110·5	110·5	0·

Experiments at slightly different primary potential differences showed that the loss in the iron varied very nearly as the square of the voltage.

The efficiency of the converters being determined, that of the dynamo alone could be found. A series of experiments was made, in which the power supplied to the pulley of the dynamo was compared with the electrical power taken up in the lamps on the secondary circuits of the transformers, and as a result the net or over-all efficiency of the system determined. The lamp load was taken at ¼, ½, ¾ and full load, and the power determined.

Efficiency of 750-Light Westinghouse Plant at Various Loads.

Load	Exciter.		Primary circuit.		Secondary circuit.		Horse-power in lamp circuit.	Power supplied to dynamo.	Loss in transformation.	*Net* Efficiency, in per cent.
	E.M.F.	Current.	E.M.F.	Current.	E.M.F.	Current.				
¼	105	9·4	1107	10·0	49·5	153·9	10·21	21·83	11·62	46·8
½	104	10·5	1107	18·9	49·6	338·4	22·5	34·4	11·9	65·4
¾	101	11·0	1113	28·6	50·0	520·7	34·9	48·0	13·1	72·7
Full	112	11·5	1125	38·1	50·9	739·8	50·48	64·44	13·96	78·3

Looking at these figures, we see that there is even at no load only a small loss in the converters themselves, but there is a very considerable loss in the dynamo armature. The twenty 40-light converters supplying the 750 lights at full load absorb only some 2,000 watts, or about 3-horse power, when the secondary circuits are open; but since the total loss is at full load equal to 13-horse power, it follows that there is a loss of 10-horse power in the dynamo at full load. From the above figures it appears, however, that at full load the commercial efficiency of the alternating dynamo in itself reaches some where about 86 per cent. Taking a commercial load diagram for the 24 hours, and reckoning the average diurnal or "all day" efficiency of such a 750-light plant, we find it to be about 60 per cent. That is to say, if such a plant were continuously supplying incandescent lamps in ordinary houses 60 per cent. of the energy given to the dynamo in the 24 hours would be represented by electrical energy in the lamp circuits, and the rest would be dissipated in the machine and converters. In actual central-station work good arrangements and proper selection of the size of unit machine would keep the working dynamo plant very nearly fully loaded at the various hours of the day, and a considerably higher average efficiency might be attained in the all-day use of such properly divided plant. Further reference will be made to the question of the reduction of the diurnal waste as far as regards the transformers and the relative advantages of transformer centres and large and small transformers.

§ 14. **Switchboards and Regulators.**—The switchboard arrangements in this system are particularly well devised. A switchboard is generally set up for each dynamo and for five or six feeders. The usual American practice is not to work the alternating current dynamos in parallel, although this is quite practicable, but to permit each dynamo to supply two or more feeding or primary circuits at full load, and then, as the load goes off, to group or gather together the feeders on to one or two dynamos in order to keep the working dynamos as far as possible fully loaded up. Figure 40 shows a switchboard arrangement (not, however, the newest form) for two dynamos and four primary lines.

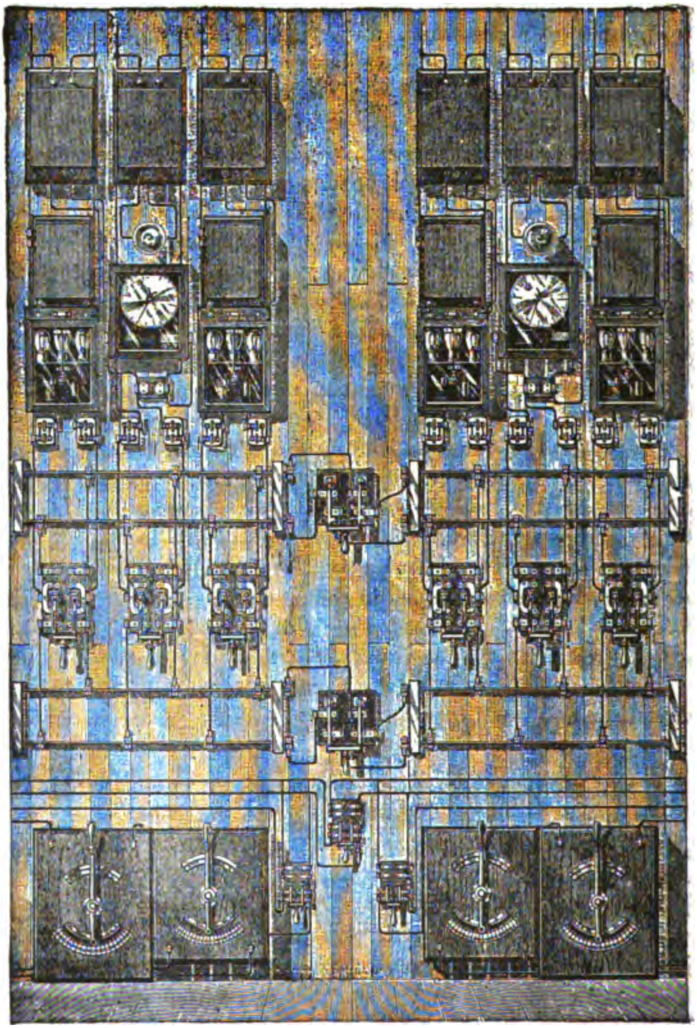

FIG. 40
Westinghouse Switchboard for Two Dynamos and Four Circuits.

Commencing at the bottom of the switchboard we see four rheostats. The two small ones at the centre control the field circuits of the exciters. It is the usual practice to provide each station having more than one dynamo with duplicate exciters, each having a capacity sufficient to charge the fields of all the alternate dynamos. Only one exciter is in use at a time, the other standing idle as a reserve. It follows, therefore, that the governing of the electromotive force of all the alternators is effected by an introduction of resistance into the field circuit of this exciter.

The control of the electromotive force of each separate alternator is effected by the introduction of resistance into the field circuits of these machines by the rheostats on either side of the middle ones. The small changing switches between the rheostats are for connecting either exciter with either dynamo at will, and for connecting the field circuits of both dynamos together. Over the rheostats are shown four sets of trunk wires, each consisting of two heavy parallel copper rods. Between each upper and lower set are three changing switches. The wires leading to the middle connection of the centre switch come from the No. 1 dynamo, whose current can be delivered to the upper or lower trunk wires at pleasure. The two outside switches of each triplet enable the primary wire attached to the centre connection of the switch to be put in connection with either trunk circuit at pleasure. Between the two sets of trunk wires are seen two multiple-arcing switches, which enable the dynamos to be run in parallel if desired, and a synchroniser or phase indicator is provided as described in connection with the Leghorn Central station (*see* § 9) to enable the dynamos to be put in parallel when in phase.

Over the trunk wires come a row of six safety catch-holders, each with double fuses and plug cut-outs. Over these safety fuses are four voltmeters, each with its attendant compensator above it. These voltmeters serve to measure the pressure at the far end of the line, and the compensator corrects the voltmeter reading for the fall in volts along the line. Between the voltmeters on the dynamo main comes the amperemeter. At the top of the switch-board is a row of small transformers, which serve to reduce the pressure for the voltmeter. It is easily seen that a large variety of possible changes are readily effected with a switch-board of this kind, and that it enables one attendant to regulate a number of feeding or primary circuits. In larger central-station switch-boards the arrangement is somewhat different. For each feeding or primary main there is a separate panel, and, by an arrangement of plug switches, any one of the whole battery of dynamos can be worked on to this feeder. Also, by a throw-over switch in the centre of this board, this feeder can be instantly thrown over on to any other selected dynamo. Hence it becomes the easiest operation to group, or collect, or change over the feeders

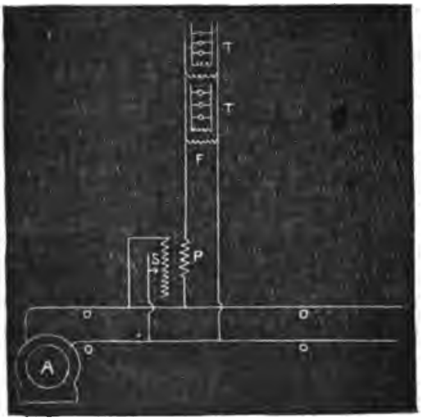

FIG. 41.—Kapp's Method of Regulating Electromotive Force at the termination of a feeder F. P is a primary coil in series with the feeder F, and S is a secondary coil in shunt off the omnibus mains O O. More or less of the turns of S are thrown into circuit as required.

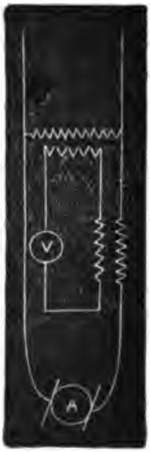

FIG. 42.

from one machine to the other; and American practice has seemed to indicate that this arrangement is, on the whole, easier to operate than working the dynamos in parallel.

When several feeders proceed from one dynamo, and on these supply lines different consumption exists than in each of the primaries, the fall in volts may require adjustment from time to time. To introduce resistance into the feeder would be a very crude device; the necessary independent adjustment of the volts at the far end of the feeder can be better obtained by a method due to Mr. G. Kapp.* Let O, O, Fig. 41, be the omnibus bars from which the feeders start. The feeder F has in series with it one coil, P, of a transformer, the other coils of which is a shunt across the omnibus bars; by inserting more or less of the turns of the coil S into circuit by a shifting contact, a little auxiliary volts are put into the feeder by the inductive action of the coil, which is in shunt across the omnibus bars. This regulating device may be so designed as to add, or be capable of adding, 50 to 100 volts to the 1,000 or 2,000 volts already on the feeder; hence, a movement of a lever enables the station engineer to adjust with great accuracy the volts at the far end of the feeder, and to do this for each feeder independently, even though all may be working off one dynamo.†

The arrangement employed for determining the volts at the far end of the feeder is essentially the same as the method already described in connection with the Ganz system. The voltmeter is in series with the secondary circuits of two transformers, one of which has its primary in series with the feeder circuit, and the other of which has its primary as a shunt across the feeder (*see* Fig. 42). The electromotive forces of these two transformers are opposed to one another. Since the secondary electromotive force of the transformer in shunt is proportional to the primary electromotive force, and since the secondary electromotive force of the transformer in series is proportional to the primary current strength, the difference between the two is proportional to V – R C, where V is the primary volt and C the primary current strength. As already explained, this difference is proportional to the pressure at the far end of the feeder, and by proper adjustment the voltmeter can be made to indicate this pressure, without any need for pressure wires run back to the station. In the Westinghouse system, the necessary transformers for this purpose are put together into a box and called a compensator (*see* Fig. 43); all that has to be done is to connect the voltmeter to the compensator.*

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* See *Proc. Inst. Elect. Eng.* London, Vol. XVIII., p. 215, 1889.

† Full details of this method of Mr. Kapp may be obtained by consulting his British Specification, No. 4345 of 1888. The variable turns on the feeder transformer may be placed either in the secondary circuit or in the primary circuit. Practically the same invention, with slight modifications, was patented by the Westinghouse Electric Company for Stillwell in a British Specification, No. 3844 of 1889. Further devices are patented by Mr. Kapp in a British Specification, No. 6728 of 1889. The Westinghouse people call this device a "booster."

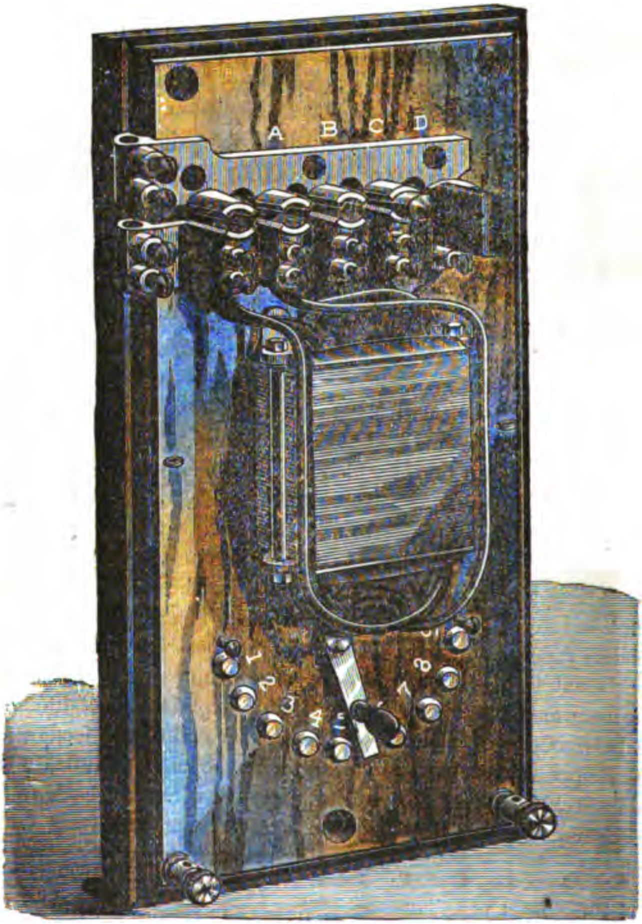

FIG. 43.—Westinghouse Compensator.

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* The essential principle of this method of measuring the volts at the far end of a line without pressure wires, and also of keeping the volts constant at the far end, irrespective of load, is explained in Dr. J. Hopkinson's British Specification, No. 3576 of 1882.

In addition to the regulation of pressure which is carried on at the station, it is necessary at theatres and in houses to be able to adjust the working electromotive force on the lamp circuits. There are two neat devices used by the Westinghouse Company for this purpose, called stage and house regulators. The stage regulator, intended chiefly for the regulation of stage lights, is shown in Fig. 44. It consists of two connected coils of wire, with an iron core not quite so long as one bobbin sliding through both. One coil may be called the series and the other the shunt coil. The diagram above (Fig. 45) shows the mode

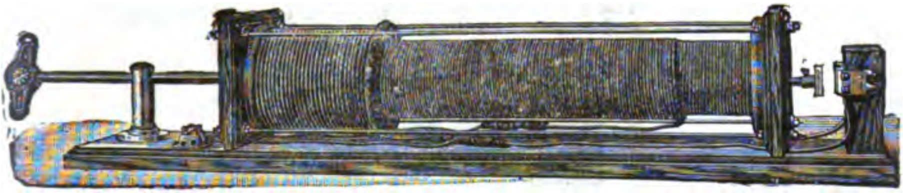


FIG. 44.—Westinghouse Stage Regulator.

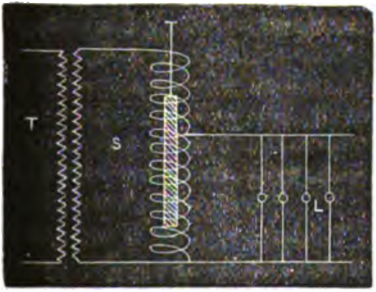


FIG. 45.—Diagram of Connections of Stage Regulator. T is the Transformer; S, the Stage Regulator; and L, the Stage Lamps.

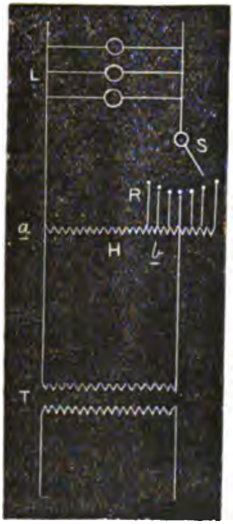


FIG. 46.—Westinghouse "House Regulator." T is the House Transformer; H, House Regulator; L, Lamps.

of connection to the lamp circuit and transformer. When the iron core is pushed wholly within the shunt coil it bestows upon it such inductance that it blocks out all current through the shunt, and the lamps will be at their full brilliancy. On gradually drawing the iron core out of the shunt coil and into the series coil the inductance of the series coil is increased, and that of the other is diminished. Hence the current through the lamps is diminished by both actions, and the lamps become less bright.

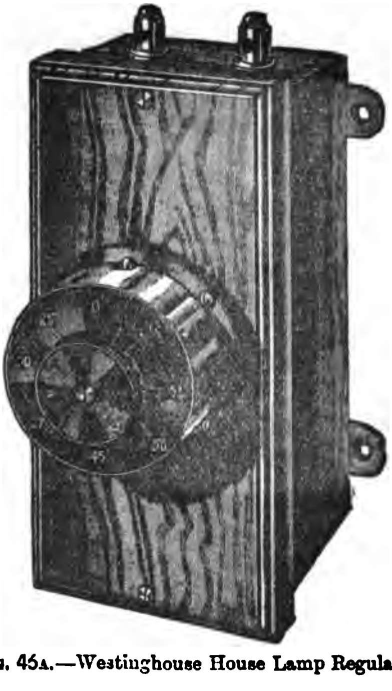


Fig. 46a.—Westinghouse House Lamp Regulator.

A somewhat similar arrangement is provided for a house regulator. Across the secondary circuit of the house transformer is a single coil, H (*see* Fig. 46), and the several sections of this coil are brought up to a revolving contact, R. By turning a handle, S, more or less impedance can be inserted in the lamp circuit. The coil also acts as an auto-converter, and can be made to raise the lamp volts slightly above the volts at the terminals of the transformer. The coils of the regulator which project as it were beyond the points *a b*, at which the transformer secondary circuit is joined in, have inductive electromotive force set up in them by the neighbouring coils, which, being added to the actual secondary or impressed electromotive force, between *a b*, make it possible to have the volts on the lamps, L, actually higher than the secondary terminal volts at the transformer. The general appearance of the house regulator is shown in Fig. 46A.

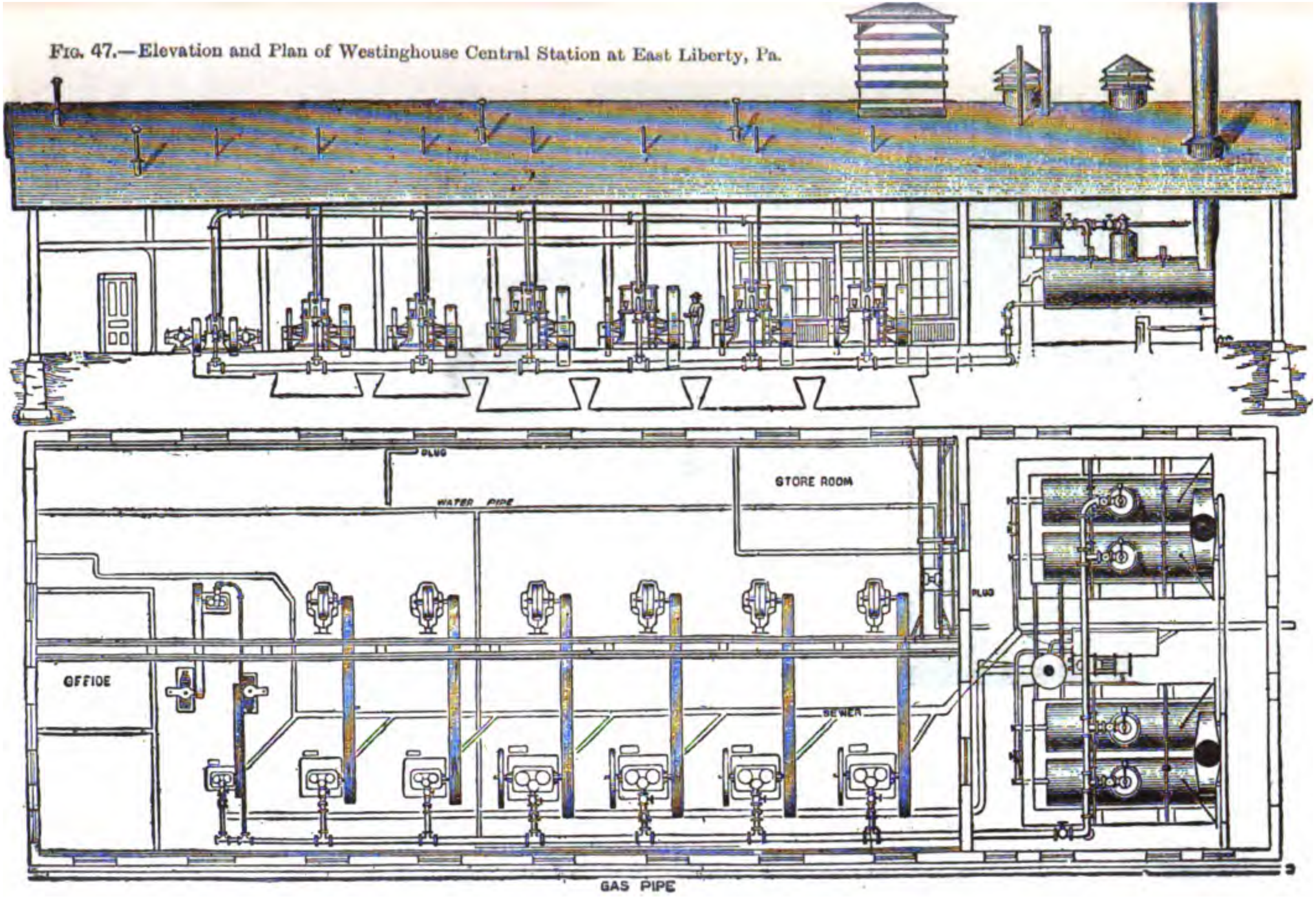
§ 15. **Typical Westinghouse Transformer Stations.**—One of the largest stations for the supply of electric current by the Westinghouse transformer system is at Pittsburgh, Pa., in the United States. The boilers at this station are of the water-tube type, heated by natural gas. The engines are of the well-known standard Westinghouse engines, and stand on square blocks of concrete or masonry, the blocks for the size used, 250 horse-power, being about 7ft. by 5ft. Five of these engines drive five alternating current dynamos, each having a capacity for 2,500 16 candle-power incandescent lamps. Besides this there is a Corliss engine, driving another dynamo. The exciters are driven from separate smaller engines. The engines driving the alternating dynamos make 250 revolutions per minute, and the dynamos 1,050. The power of the engines is conveyed to the dynamos, which are placed on a floor above, by belts. Each dynamo is fixed on a sliding bed, so that the belt can be tightened. The general construction of these alternators has been described in a previous section. From the dynamos the mains are run to the switch-board in troughs cut in the joists supporting the floor. The switch-board at Pittsburgh is about 9ft. high and 14ft. long, and stands away from the wall of the dynamo room about 3ft. to enable access to be had behind it for making all connections.

One single exciter dynamo is used, another being in reserve, to provide exciting current for several machines, and convenient switches are placed on the board to enable the excitation to be effected by either of the exciters. The general details of the board, as well as the arrangements for measuring and regulating the pressure at the far end of each feeder, have been already described. This station furnishes current for about 13,000 incandescent lamps (1890).

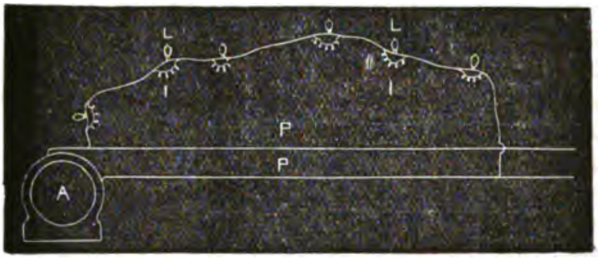
A very typical Westinghouse station, operating overhead primary conductors, is that at East Liberty, Pa., U.S.A. The service from this station covers a very extended area, comprising the business portion of the city, which lies at an average distance of half a mile from the station, ramifying through an extended series of residence streets, and carrying a special line to a distant suburb in which the last lamp is four-and-a-quarter miles from the dynamo. The arrangement of the building is shown in Fig. 47. A one-storied brick building contains offices, stores, dynamos, and boiler room. The plant has an aggregate capacity of about 8,000 lights. Dynamos and engines are on the same floor, every part of which is under the eye of a single attendant. The engines and dynamos stand on brick foundations. Each engine is belted to its own dynamo. The steam pipe is brought along overhead, and the engines exhaust into a main laid in a covered trench underneath the floor. Two exciters are provided as shown on the left of the dynamo room, each adequate to supply current to the entire station, and each driven independently by its own engine. Only one exciter and engine is operated at once. The position of the exciters and engines is such that by changing a belt either engine can drive either exciter. Two overhead cranes traverse the whole length of the buildings over the engines and dynamos. Using natural gas to fire the boilers, attendance is reduced to a minimum, and one attendant in the dynamo room can give all necessary attention to the engines, dynamos, exciters, and switch-board. The reduction of labour to a minimum is especially made an object in the design of these American stations.

In connection with these transformer stations, a system of street incandescent lighting has been worked out, which is very efficient, and enables a large amount of street lighting over scattered areas to be taken up, but which would not be remunerative if primary mains and transformers had to be placed along the whole route. Starting anywhere from one primary main or feeder, P (*see* Fig. 48), a single line is run following the route of the proposed street lighting; and at every place where a street light, L, is required, an impedance or choking coil, I, is placed having a low-resistance series incandescent lamp across its terminals. This line is then so

Fig. 47.—Elevation and Plan of Westinghouse Central Station at East Liberty, Pa.



run that it terminates at some distant spot on the other member of that same primary line or feeder. Suppose that



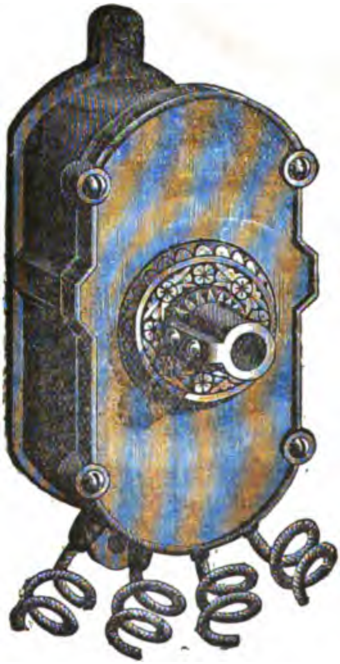


FIG. 49.—Westinghouse Impedance Coil for Series Lighting.

the primary pressure is 1,000 volts, and that 10 volt low-resistance lamps are used, there can be 100 such coils and lamps on that series line. The impedance coil is contained in a box on the bracket that carries the lamp (*see* Figs. 49, 50). If any lamp breaks, the impedance coil is thereby thrown into the circuit and lowers the current just by that amount which keeps the rest of the lamps on that circuit from being over burnt. Hence the breakage of any of the lamps does not affect the light of the rest, nor does the removal of one lamp in any way affect the operation of the others, although the lamps are all in series.

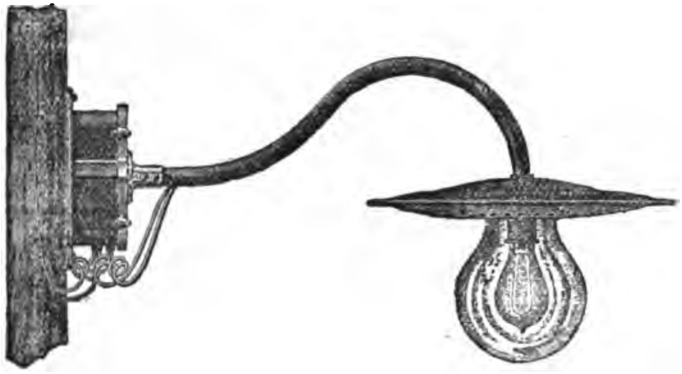


FIG. 50.—Series Street Lamp and Impedance Coil.

§ 16. Westinghouse Central Stations in England.—Sardinia Street.—One of the largest of these, now completely finished and in active operation, is that in Sardinia-street, Lincoln's Inn-fields, London. The erection of this station was begun in August, 1888, and on September 21, 1889, current was first supplied from it. The dynamo plant and engines were constructed by the Westinghouse Company, and it was arranged and fitted up by this last-named Corporation for the Metropolitan Electric Supply Company of London. The Sardinia-street station is a very complete and typical station for the supply of electric currents on the alternating-current transformer system. It consists of a substantial two-storey building, in the construction and design of which the highest possible architectural and engineering skill has been applied to cope with the difficulties which might arise from noise or vibration in a building so placed in the centre of a closely inhabited Metropolitan area. It may broadly be described as a box within a box; that is to say, the central portion, or machinery rooms, are enclosed in a building which is itself contained in a closed-in space; and the communication of aerial vibration is thus greatly limited by the double walls with intervening space which separate what may be called the vitals of the station from the external space. The communication of vibration through the foundations has been prevented by the most carefully arranged methods, and, generally speaking, the whole problem of installing a steam plant of the magnitude required in such a manner as to avoid the difficulties inherent in such a work, has been dealt with in a manner which speaks highly for the skill and experience invoked. The general plan of the station is shown in Figs. 51, 52 and 53. The chimney shaft is of white glazed brick externally, and the whole building is lined internally with white glazed brick, which gives it a very clean appearance. The ample space in the dynamo-room, engine-room, and boiler-house render the working of the station most comfortable to the staff.

On the ground or entrance floor are placed the engines (*see* Fig. 52). The dynamos and exciters are on the floor above, and are driven by belting passing up through the floor. The boiler-house is on a lower level than the engine-room, and the coal store is so arranged that the coal is shot down from the street level direct into it.

Entering on the engine-room level, which opens into a covered yard, we find a double row of Westinghouse compound engines. Five of these engines are each of 250 horse-power, and five are of a rather larger size, making in all a provision for the actual production of about 3,000 horse-power. Behind one series of these main engines stand three Westinghouse engines of 65 horse-power, each of which serves to drive the exciter dynamos. The main engines have high-pressure cylinders of 14in. diameter, and low-pressure cylinders of 24in. diameter and 14in. stroke, and are technically known as 14 × 24 × 14 engines. The exciter engines have high-pressure cylinders of 10in. and low-pressure cylinders of 18in. and 10in. stroke. These Westinghouse engines are so well known that space need not be occupied by detailed description

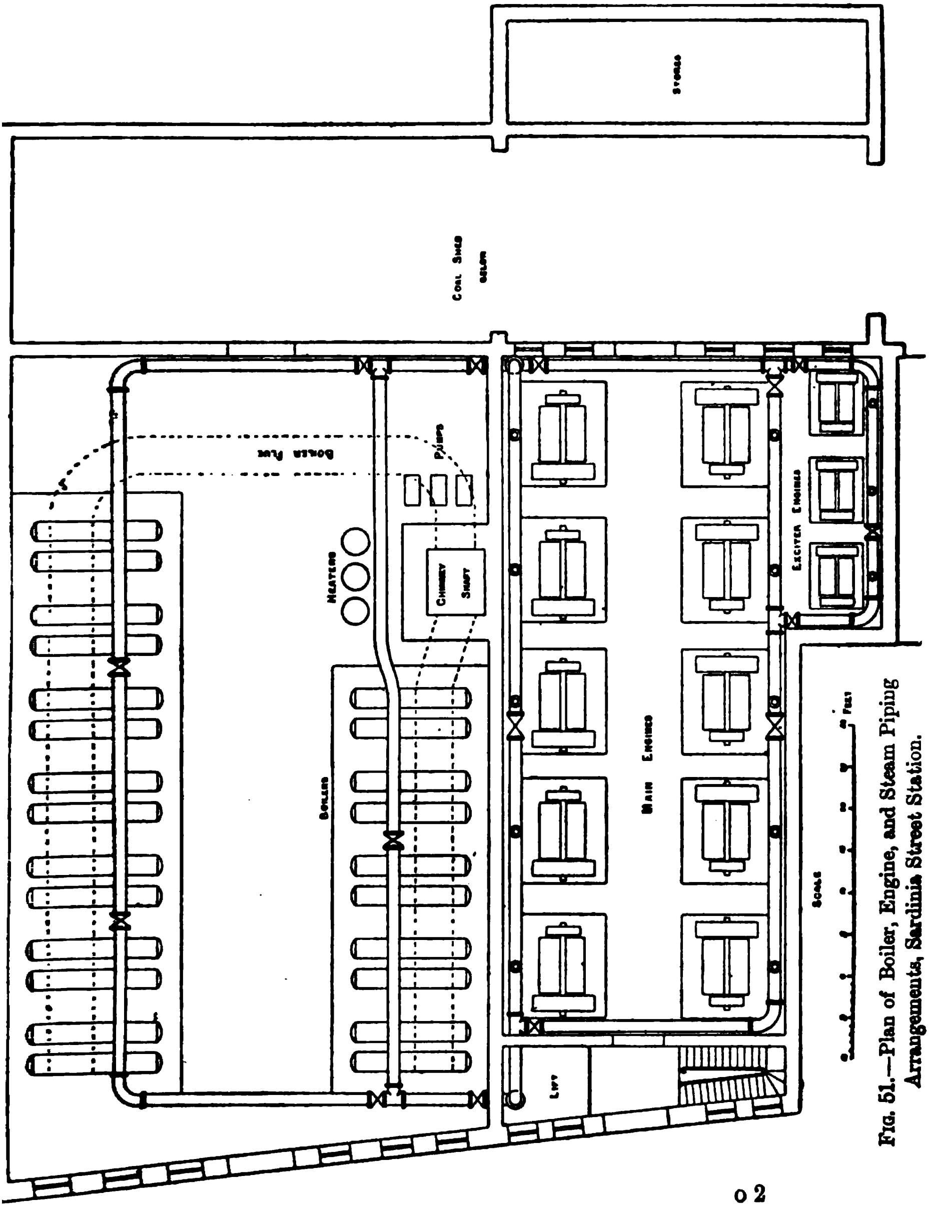


Fig. 51.—Plan of Boiler, Engine, and Steam Piping Arrangements, Sardinia Street Station.

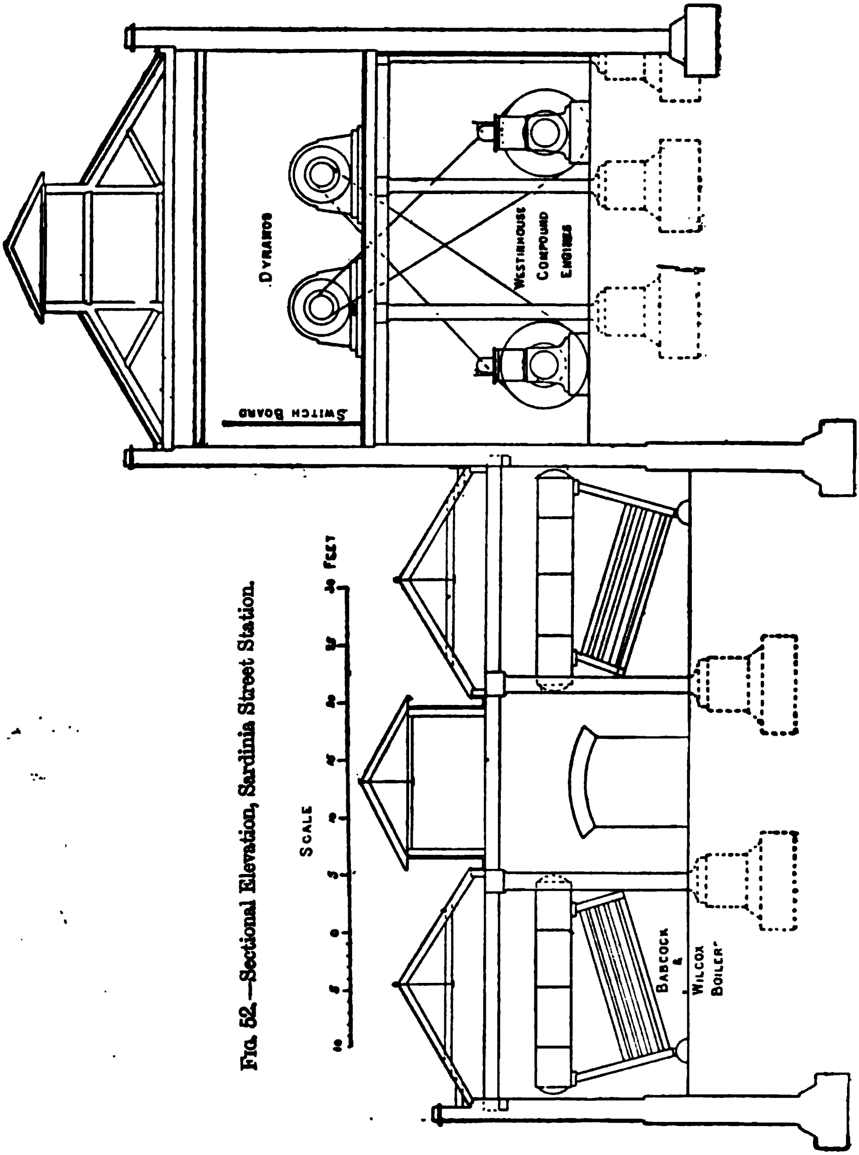


FIG. 52.—Sectional Elevation, Sardinia Street Station.

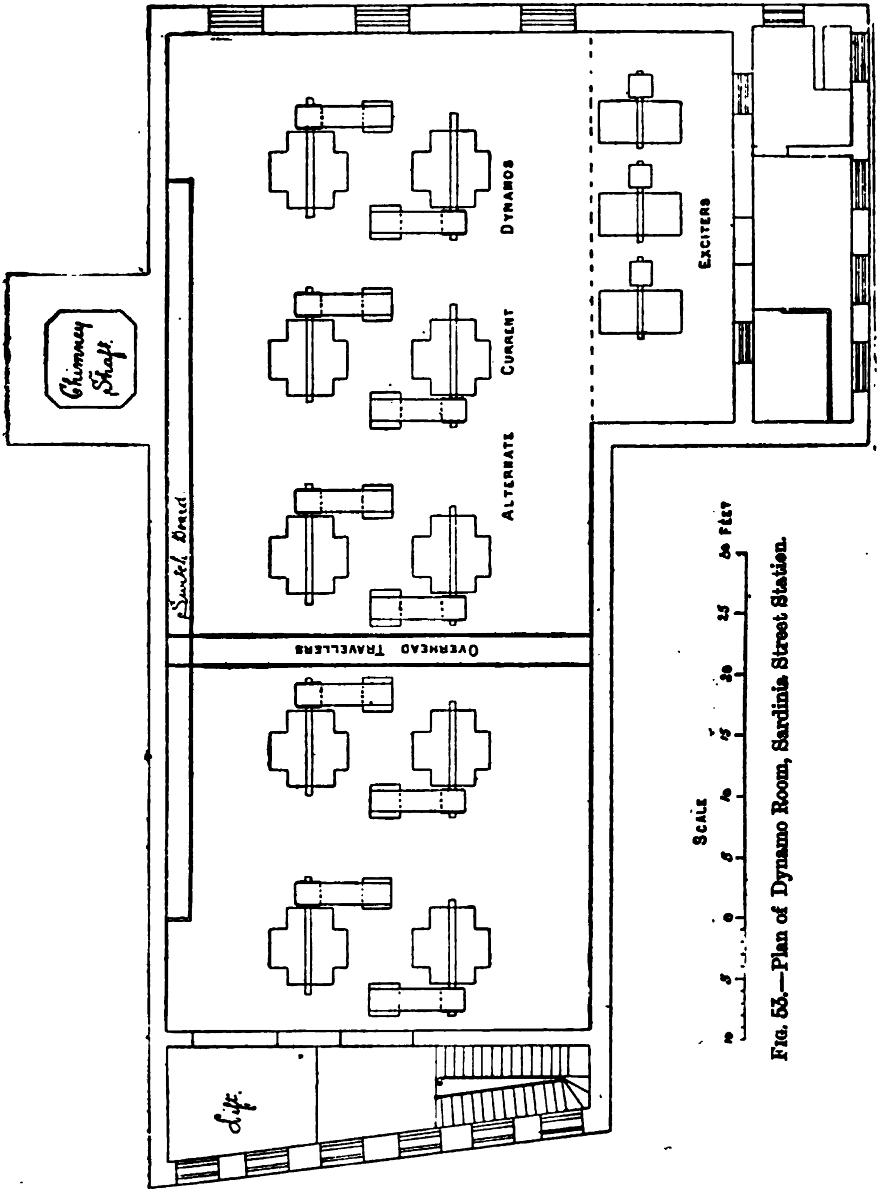


Fig. 53.—Plan of Dynamo Room, Sardinia Street Station.

of them. They are high-speed engines, making 200 revolutions per minute, and having a piston speed of 653ft. per minute. At Sardinia-street they are worked non-condensing. Each engine is built up on a brick and concrete platform which rests on a bed of felt and sheet lead, this in turn reposing on the concrete foundations. By this device the communication of "thump" through the foundations is prevented. This series of separate engines forms a steam plant which can be divided up and operated in such a manner as to secure that the engines actually in use are being worked as nearly as possible at their full power. Each engine drives its own alternating current dynamo on the floor above by means of a leather belt. These belts are 20in. in width and made of the finest leather, spliced with bevelled joints to avoid any double thickness at a joint. The engines take steam from a ring steam main and exhaust into a single exhaust pipe large enough for 3,000 horse-power. Each section of the ring steam main can be isolated by stop valves, so that any section can be cut out without affecting the rest. Descending down one flight of steps into a lower level we find ourselves in the boiler-house, in which are erected twelve Babcock and Wilcox water-tube boilers, each capable of evaporating 6,000lb. of water per hour. These boilers are set in two rows face to face down the sides of the boiler-house, the length of the house being about 100ft. Ample space to stoke is left between the furnaces; and down the centre of the gangway runs a tram-line, on which the coal trolleys are run from the coal store to the furnace mouth. Underneath this gangway are the blow-off tanks and piping.

The boilers are supplied with water by three Worthington steam-pumps, any two of which will do the whole work; and the feed is so arranged that it can be taken either through the feed-water heaters, of which there are three, or by a by-pass direct into the boilers. The boilers are fed from both drums. The water tank is large enough for twelve hours' work at full load, and there is also a water supply direct from the mains. The boilers can be thus supplied either direct from the mains or from the water tank, and the water can be taken either through the feed-water heaters or direct into the boilers. The floor of the boiler-house is about eight or ten feet below the level of the street, so that dirt cannot be carried into the engine-room. The boiler-house has a glass sky-light roof, and is comfortable and spacious. At the end of the boiler-house is the coal store, capable of holding about 500 tons of coal. Into this store the coals can be shot down from the coal carts in the street above by shoots. There it is handled into the coal trolleys and goes at once by the boiler-house tramway to be delivered at each ashpit. It is thus seen that the minimum of labour is required both in stoking and in coal handling. The boilers all feed their steam into a ring main, the general plan of the steam piping being shown in Fig. 51.

Ascending on to the first floor, above the engine-room we find ourselves in a large and well-lighted dynamo-room (*see* Fig. 53). Here are ten Westinghouse alternate-current dynamos, of 125 kilowatts output each, providing, therefore, for a total output of 1,250,000 watts, or for a supply of 20,000 50-watt lamps, all burning at one time. These dynamos are respectively driven by the belting coming up from the associated engine on the floor below. The belts and pulleys are covered in with belt shields. Each dynamo generates an alternating current at a pressure of about 1,050 volts when running at its normal speed of 1,030 revolutions per minute. These dynamos are technically known as the "No. 3" size. They are bolted down on strong wooden frames, and have the usual belt tighteners and screws. All moving parts of the dynamos are supplied with oil from sight-feed lubricators, which are themselves fed from an oil tank placed at a higher level. From this oil tank proceed a system of oil pipes to each dynamo. The waste oil runs away downstairs by waste pipes; it is cleaned, filtered, and pumped up again to the oil tank by a small pump. By this excellent arrangement, which is characteristic of American engineering, the use of oil cans is rendered entirely unnecessary.

The detailed description of this size and type of Westinghouse alternator has been given in § **12** of this chapter. A few further details of its construction may here be given. The armature is composed of sheet-iron discs, which are punched out in the centre so as to leave wheel-shaped iron laminæ (*see* Fig. 54). These sheets are put together without paper between them, but are previously, however, slightly oxidised or rusted. It is found that the thin layer of oxide has sufficient electric non-conductivity to arrest eddy currents, but yet not any disadvantageous magnetic non-conductivity. These iron discs are assembled on the steel shaft, and compressed by massive screw-nuts between end plates. The soft-iron plates are carefully annealed after being punched, so as not to require touching with tools after this annealing. On this iron core is laid a layer of asbestos and mica, and then on this the flat, link-shaped coils of insulated wire. These coils consist of one layer of wire formed into a flat coil of 13 turns. Each coil is 27in. long in the straight part, 5·5in. wide; and the aperture of the coil, which is filled in with a wooden lathe, is 1in. wide (*see* Fig. 55). Hence there are 27 × 26 = 702in. of active wire on each coil. These coils are laid on the drum, and are just so long that the curved ends of the coils can be bent over the end of the drum. Sixteen such coils are laid on, having one-quarter of an inch space, occupied by a wood strip,

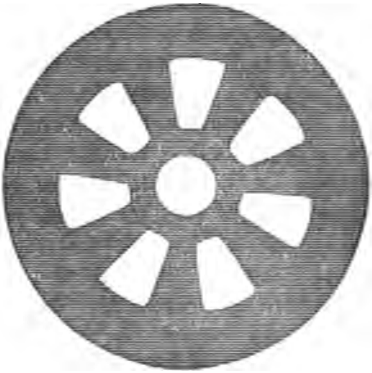


FIG. 54.—Sheet-Iron Disc of Westinghouse Armature Core.

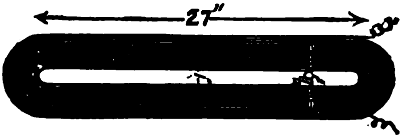


FIG. 55.—Single-Flat Coil of Westinghouse Armature.

between adjacent coils. The coils are then bound on the drum with brass wire, the wire of the coils being protected by asbestos and mica insulation. The surface of the core is quite smooth, and the flat wire coils are kept in position and driven round simply by the friction due to the binding wire. The coils on each half of the drum are joined up in a series of eight, and the two series are joined together in parallel. Hence, each coil contributes 125 volts to the electromotive force, which is at the rate of less than six inches of wire to the volt. The wire of the armature coils is double cotton-covered and insulated with a special insulating varnish. The ends of the coils where they are turned over the flat end of the drum are defended by bronze shielding plates. The whole armature is thirty inches in diameter over all. In addition to the end plates another disc is provided at one end, with radial strips which act as a centrifugal fan and draw air through the apertures in the core to assist in keeping it cool.

The armatures of all the machines being exact facsimiles are interchangeable. By means of an overhead traveller, which runs the whole length of the dynamo-room, it is a matter of a few moments to lift off the top half of the field-magnet of any dynamo, lift its armature out of its bearings, and replace it by another. This construction of armature is both simple to repair, and admits of very high insulation being attained in practice. The ring-shaped field-magnet frames carry sixteen magnet poles projecting inwards. These poles are solid cast iron, and are 27in. long, 2·5in. wide, and 8in. long. On to these poles are slipped the shells or frames carrying the field-magnet coils. These poles are alternately N. and S.

The field magnets are excited by continuous current from three shunt-wound exciters. Each of these exciters, which is driven by its own engine, can furnish a continuous current of 300 amperes at an E.M.F. of 100 volts; and as each alternator only requires 27—28 amperes to excite it at full load, it is seen that one exciter can feed the whole battery of ten alternators. The exciters are ordinary horizontal double-magnet shunt-wound continuous-current machines. They have pulleys with paper driving surface, and are the usual form of Westinghouse exciters.

The arrangements in the dynamo-room for effecting all the necessary interconnections and changes between dynamos, exciters and feeders, have been elaborated with great care, and the methods in use at Sardinia-street are the outcome and final result of an immense and expensive experience in other places. The process of evolution of machinery is always, or almost always, from the complex to the simple; the process of discarding or shedding off unnecessary organs, and reducing the parts to the fewest possible, is one in which advance shows itself.

On entering the dynamo-room of the Sardinia-street Station, we are struck at once by the immense and handsomely finished switchboard. It occupies a great part of the length of one side of the dynamo-room, and is about 54 feet long, and 11 feet in height. It stands away from the wall by about a couple of feet, allowing sufficient room for workmen to pass behind it, and to make or renew all the multitudinous connections which are made by highly insulated cable behind this board. The front of the switchboard is divided into twenty panels, the base of each panel being of enamelled slate framed in polished wood. From the dynamo-room proceed twenty feeders, or primary mains, and as there are ten alternators and three exciters, the combinations which have to be effected are as follows:—(1) Any group of alternators must be capable of being excited by any exciter. (2) Any one or group of feeders must be capable of being worked off any alternator or group of alternators. (3) Any given alternator must be capable of being made the "stand-by," or reserve machine, to any working dynamo or group of dynamos; and, lastly, any group of alternators must be capable of being worked in parallel together on any primary main or mains. (4) All these changes have to be made instantly, certainly, and without confusion, by one person.

We shall best explain the principle on which this is done by giving a diagram and description of *a small portion* of one-half of a single panel of the switchboard. We shall limit our attention to a combination, first, of a single feeder and three alternators, and show how these changes are effected. Referring to Fig. 56, let 1, 2, 3, 1′, 2′, 3′, be the leads from three alternators, No. 1, No. 2, and No. 3. These leads are terminated on brass plug blocks, *a*, *b*, *c*, *a*′, *b*′, *c*′, fixed on the panel. On either side of this group of blocks are four common bars, *h*, *g*, *h*′, *g*′, and plugs can be inserted in the holes to connect *a*, *b*, *c*, &c., with *g*, *h*, &c. The primary main F F′ terminates on the centre of a duplex double-pole switch between the bars. When this switch is thrown up it connects F F′ with bars *g* and *g′*. When it is thrown down it connects F and F′ with bars *h* and *h′*. The handle of this switch has three positions in which it will stand firm: 1st, one in which F and F′ are both disconnected from G and G′, and also from H and H′; 2nd, an upper position, or one in which F and F′ are connected to G and G′; and 3rd, a lower position, or one in which F and F′ are connected to H and H′.

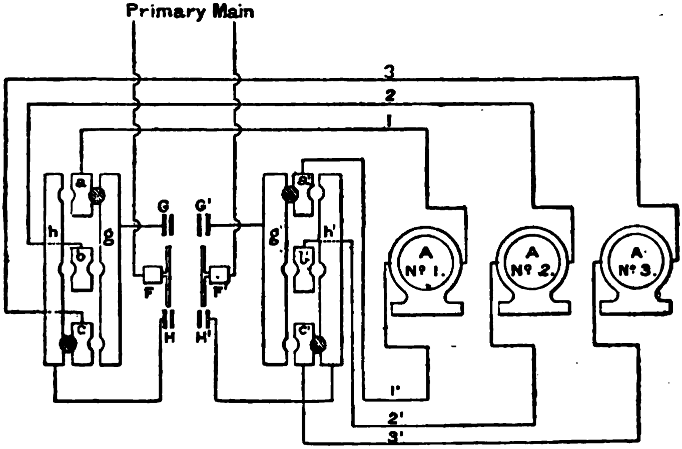


FIG. 56.

This being understood let us suppose that plugs are inserted in the four holes marked with a shaded circle, and let the centre switch be in the upper position. Then alternator 1 is connected with the primary main F, F′, and may be considered to be working on it. Let alternator No. 3 be kept turning slowly round, and let us suppose something goes wrong with No. 1 machine. The engineer simply calls down for the alternator No. 3 to be run up to full speed, which can be done in a few seconds. He then snaps over the centre switch from top to bottom position, and the instant result is that the main line is changed over from machine No. 1 to machine No. 3. Let us also imagine that it is required to run alternators No. 1 and

No. 2 in parallel, and to have No. 3 as a reserve. This can be effected by putting plugs in the holes joining blocks *b* and *b* to bars *g* and *g′*, in addition to those already in.

This being clear, all that remains to be said is that at Sardinia-street each semi-panel of the switch board contains two such rows of ten blocks, like *a*, *b*, *c*, &c., and four bars like *g*, *h*, *g′*, *h′*, and a centre switch, as shown in Fig. 57.

Each complete panel is the double of this, and supplies a pair of primary mains, making the two to each dynamo, and the ten double panels correspond to the twenty mains. On looking at the board when the dynamos are working we see a set of plugs plugged-in to join the dynamo blocks *a*, *b*, *c*, &c., to the omnibus-bars *g* *g′*, &c., and we see a plug in the corresponding holes of all the panels, which is the plug belonging to a spare machine. We can thus have the feeders grouped in any way on the working dynamos, and we can have a spare machine which, as it were, waits on all of them, and is ready instantly to take the place of any working machine that gives out. Thus we may suppose five feeders—1, 2, 3, 4, and 5—are working off dynamos No. 3, 7, and 9, grouped as follows:—No. 3

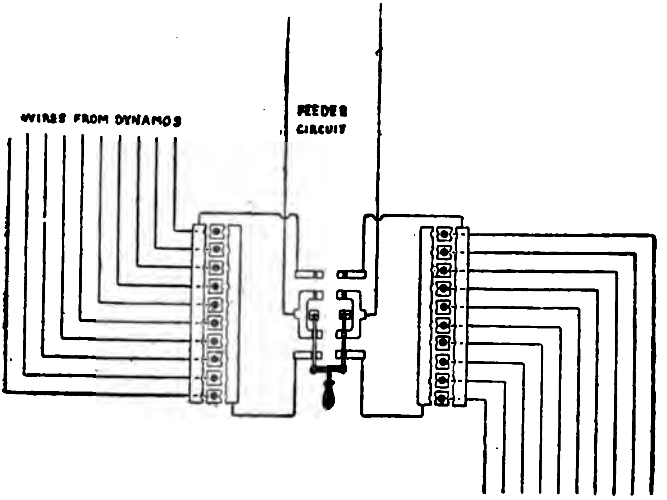


FIG. 57.

works feeders 1 and 2, No. 7 works feeders 3 and 4, and No. 9 works feeder 5. Also let dynamo No. 5 be a reserve machine turning slowly round. If No. 3 dynamo were to be found to be getting hot bearings, No. 5 reserve would be started up, and switches of panels No. 1 and No. 2 thrown over. The reserve machine could then step into the shoes of No. 3. Or, if No. 3 machine were to be found to be overloaded, one of its feeders, say No. 1, could be thrown over on to a reserve machine. It will thus be seen that the possible combinations are endless, and that the engineer need never be in a "tight place" by reason of not being able to re-adjust the load, or to relieve a particular machine unequal to its work.

We have next to describe how the exciters are coupled in. This is rendered plain by a diagram of connections engraved on a brass plate and fixed to the switchboard. This diagram is given in Fig. 58. The connections are shown in Fig. 59.

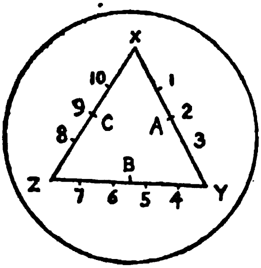


FIG. 58.

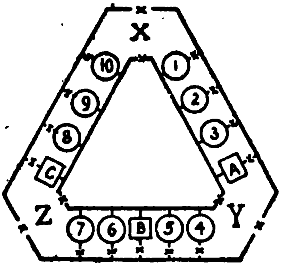


FIG. 59.

Let three pairs of mains be arranged between three double pole switches, X, Y, and Z. When all these switches are closed it forms a closed circuit. Between these mains are joined in parallel all the armatures of the three exciters A, B, and C, and all the fields of the ten alternators, each, however, being capable of being cut out by its own private double pole switch. It will then be seen that by suitably closing the private switches (marked by a small cross in the diagram), and by manipulating the switches X, Y, or Z, the exciters can be used to excite any group or groups of the alternators in a very varied manner. The five centre panels of the switchboard are devoted to these exciter switches, and the centre panel of all has on it the switches X, Y, and Z. If, therefore, anything goes wrong in the dynamo-room, the engineer in charge flies to the centre panel of the board. From this spot he can see the whole dynamo-room, and every dynamo has its number painted conspicuously upon it. Hence he can see at once what to do to take that machine out of circuit.

Over each panel of the board and in connection with each primary main is an amperemeter, a voltmeter and the voltmeter compensator. This last device which enables the voltmeter in the station to read the volts at the far end of the primary main has already been fully described.

There is also a standard station voltmeter, by which all the others are adjusted. Underneath the panel there are the variable resistances to be inserted in the field circuit of each alternator as required, and the resistances to be inserted in the field circuit of the exciters for regulating the exciting current. By these resistances the exciting field of any alternator can be controlled independently of all the rest, and the volts at the far end of its associated mains kept to the standard voltage. Also by the resistances in the fields of the exciters the electromotive force of any simultaneously excited group of alternators can be raised or lowered as required. It will thus be seen that a vast amount of thought and skill has been brought to bear on the design of these arrangements with the object of reducing to a minimum the labour required.

The distributing system of mains in connection with Sardinia-street is an underground system. Highly insulated leads, covered with vulcanized indiarubber, are drawn through iron pipes laid under the footways or roadways.

The underground conductor system employed consists of iron conduits into which are drawn highly insulated mains, mostly Silvertown electric light cable (Class L), the size chiefly in use being $\frac{19}{16}$. The pipes are of iron, cast vertical and in nine foot lengths. These iron conduits are laid under the footways and split T pipes are inserted for the customers' "take off" but no junction or jointing boxes are used. The general system of main laying is to lay the mains in "rings," drawing in the cable in short engths, and taking both ends of each such length into the consumers' premises. The diagram in Fig. 60 will make clear the arrangement followed. This arrangement in "rings" ensures that each customer gets his supply in duplicate, and the "ring" can be cut anywhere without interfering with the continuity of the supply of any consumer; and any section can be cut out and tested or replaced at any time. As the present price of coal necessitates working at a current density of about 600 amperes per square inch, it is clear that even if the "ring" is cut anywhere the cable will not become overloaded. Each of the sections or lengths from customer to customer is without joint, and no making of T joints (always a difficult matter) is required.

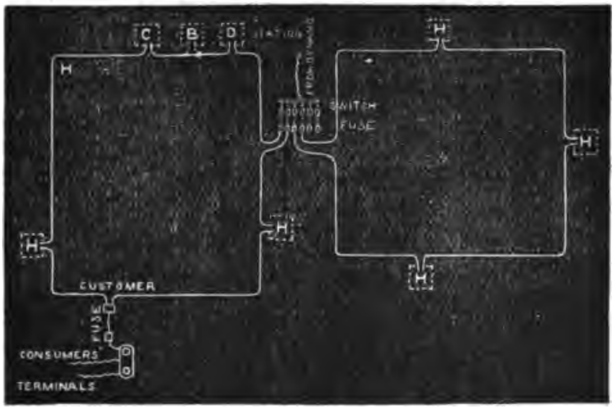


FIG. 60.—The Metropolitan Company's System of Ring Mains.

If a house at B (Fig. 60) requires a supply the main from C to D can be disconnected from the cut-outs even with the current on, and one or both the halves of that section of the cable drawn out of the conduit and replaced by new lengths, the old lengths being returned to stores and used for other similar work; or one of the lengths may be drawn through with a new short length of the proper dimension attached to the end. It only remains to add that Westinghouse transformers are used, although not exclusively, in connection with these mains, and that the transformers are placed in customers' premises and distributed over the network of primary mains.

§ **17. Westinghouse Alternate-Current Arc-Light System.**—In addition to the above-described transformer systems of lighting by incandescent lamps, the Westinghouse Company have designed a system of series-arc-lighting by alternating currents.

This system consists in operating a constant-current alternator on a main circuit which passes through converters suitable for the number of lamps to be operated at any one point. The system has been worked out in a very complete manner, both as regards the dynamo, the lamps, and accessories.

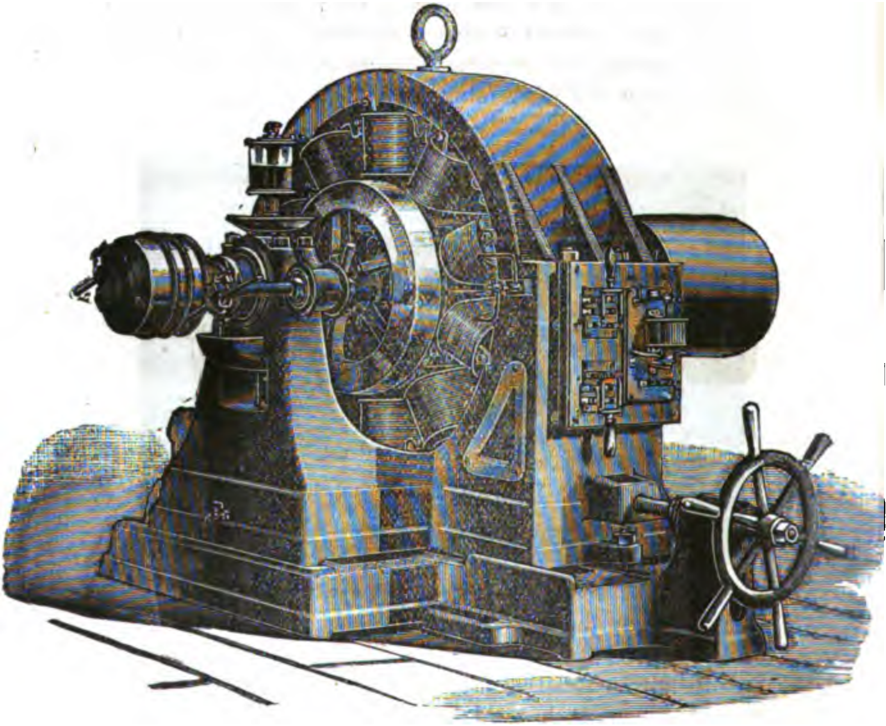


FIG. 61.—Westinghouse Constant-Current Alternator for Arc Lighting.

The dynamo very closely resembles the Westinghouse alternating incandescent machine (*see* Fig. 61), but its distinguishing feature is to be found in the construction of the armature.

The field magnets, like that of the incandescent light machine, are composed of a series of solid iron radial pole-pieces having alternating polarity, projecting inwards from a ring frame. On these cores are a series of bobbins, each independent of all the others, which are wound on shells and can be readily replaced if injured. The field may be charged from a separate exciter, in large stations, wherever a separate exciter is constantly running, or the machine can be constructed so as to be self-exciting.

The magnet frame parts along a horizontal plane through the shaft, and so admits of the upper half of the dynamo being readily removed for the replacement of an armature or field coil.

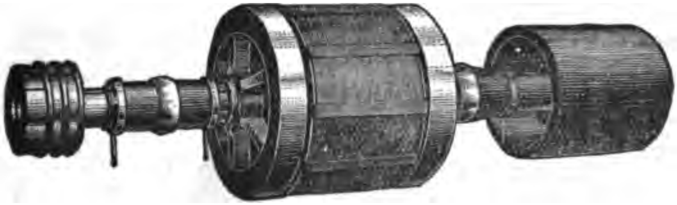


FIG. 62.—The Westinghouse Arc Light Alternator. Perspective view of Armature.

The dynamo is reversible on its base, and can run in either direction; hence it is adapted to all situations. It stands upon a fixed base, upon the ways of which it can be shifted by means of a belt-tightening screw.

Five sizes of arc-light dynamos are manufactured, having the following capacity, rated in lamps of so-called 2,000 nominal candle-power each:

No. 00,	25 Lights,	...	Floor Space,		55⅜in.	× 43¾in.
,, 0,	40 ,,	...	,,	,,	65in.	× 62½in.
,, 1,	60 ,,	...	,,	,,	5ft. 8½in.	× 73¾in.
,, 2,	125 ,,	...	,,	,,	7ft. 9in.	× 79¼in.
,, 3,	250 ,,	...	,,	,,	9ft. 3in.	× 83in.

The principle of conversion of current renders it possible to build dynamos of the large capacity above given without introducing dangerously high potentials in the line wires.

The armature is shown in perspective in Fig. 62, and in transverse section in Fig. 63. It will be noted that in this case the armature coils are not, as in the incandescent light dynamo, in the shape of flat coils placed on the periphery, but consist of oblong coils (Fig. 64) which are wound separately on

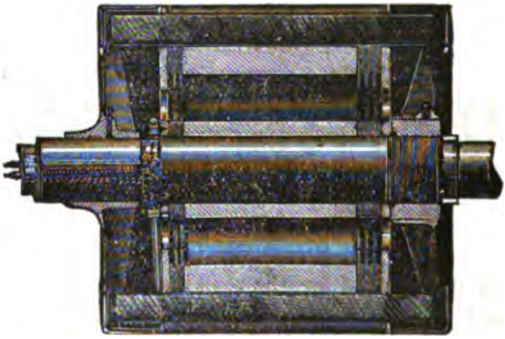


FIG. 63.—The Westinghouse Arc Light Alternator. Transverse section of Armature.

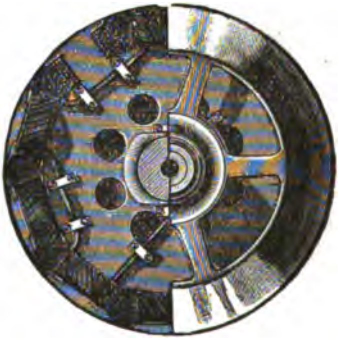


FIG. 63A.—Details of Armature.

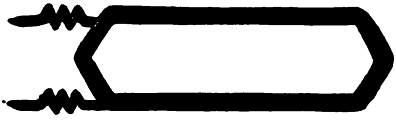


FIG. 64.—The Westinghouse Arc Light Alternator. Armature Coil.

formers, and then by means of a clamping tool (Fig. 64A) are squeezed into position around projections on the cores of the armature, which are provided with overlapping iron teeth. After the coils have been placed in position the spaces between the teeth are filled out with wedges, which are dovetailed and slid in from the side, so that no further fastening is required to keep the coils or the wedges themselves in position. The peculiar Pacinotti construction of the armature core with the overlapping teeth has the effect of maintaining the current constant at all loads, so that there is no regulating apparatus whatever required for that purpose.

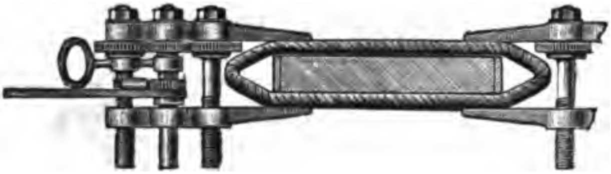


FIG. 64A.—Clamping Tool.

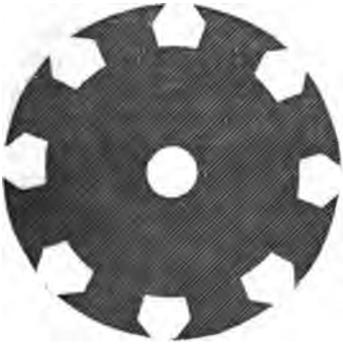


FIG. 65.—Form of Soft Iron Disk used in building up Armature of Westinghouse Alternator for Constant Current.

The armature core is built up of piles of thin wrought-iron sheets stamped out to a shape shown in Fig. 65, having teeth so designed, and of such length, that they slightly overlap the distance between two consecutive pole-pieces, so that one tooth is not out of the field of any one magnet before another enters that field.

The body or core thus made of these laminated iron plates punched out of the sheet metal, when clamped together, has thus deep undercut channels along the face for the reception of the armature coils. The ribs of metal which separate the channels carry the armature coils. These coils are independent and detachable, and are securely wedged in place, as stated, by blocks of seasoned wood driven into the space between them, and held in place by locking under the projecting shoulder of the rib. The necessity of exterior insulation, and the wrapping of the armature with binding wire, is thus entirely avoided. The absence of surface-winding makes it possible to run the armature much closer to the field-poles than is practicable in other forms of construction. As is well known, the general effect of decreasing the clearance between armature and fields within certain limits is to increase the efficiency of the dynamo. The form of construction here employed makes it easy to take full advantage of this fact. Brass shells cover each end of the armature, protecting the ends of the coils.

At the side of the dynamo there is an apparatus consisting of a solenoid with a single core. It is a short-circuiting apparatus, and its object is to protect the machine from the results of a break in the line. By this means the counter electromotive force generated in the armature is such as to cut down the heavy current to the normal strength, so that no dangerous heating of the armature coils can take place. The apparatus is so constructed that an excess of electromotive force generated in the armature, such as would be caused by a break in the line, causes a spark to pass between two points; this allows sufficient current to pass to energize the solenoid, which pulls up its core and makes contact between two points that short-circuit the armature.

There is still another safety device of the same nature, which consists of two metal points placed opposite each other on the armature shaft and connected respectively to the collector rings. Upon the current exceeding a certain value the spark formed between these two points causes a short-circuiting of the machine, and a consequent cutting down of the current, due to the increased self-induction.

The machines now built and in course of construction vary in capacity from 25 lights to 240 lights. The speeds of these machines are considerably lower than those employed in the incandescent system, and the number of alternations per second is also far below that of the former, the average number approximating 7,500 alternations per minute, as compared with 16,000 for the incandescent machines. The machines Nos. 2 and 3 are provided with two sets of windings connected to two pairs of collectors, so that two independent circuits can be run from one machine.

Coming now to the apparatus intermediary between the dynamo and the lamps, we find it to consist of converters which do not, of course, differ in principle from those used in connection with the incandescent system of distribution; but for this particular purpose converters of a peculiar construction are in some instances desirable. In ordinary incandescent systems the primary and secondary of the converter are usually so designed that the ratio of reduction of potential between them is comparatively a high one, usually such as 20 to 1. In this system, however, a series of converters of various capacities are designed, in which the ratio of the primary to the secondary is as 1 to 1, and in others as 1 to 3. The windings in the 1 to 1 converters are evidently identical for the primary and secondary. Though on first consideration this might be considered a curious condition, the reason therefor will become apparent when it is considered that by the employment of such converters no greater potential is admitted to a building in which there is one lamp, for instance, than is required for that particular lamp, and leaving the same perfectly safe to be handled, as the potential required for each lamp does not exceed 50 volts.

The lamps employed in connection with this system are of two general types, known as the long and short lamps, and designed respectively for outdoor and indoor use. The distinguishing feature of these lamps (*see* Fig. 66) consists in the fact that they are designed to burn flat carbons whose life approximates to 40 hours in the case of the long lamp, and to a somewhat shorter period in the case of the short lamp. Thus, in the long lamps two carbons are employed, the dimensions of which are 9½in. by 2in. by $\frac{7}{16}$in. In the short lamp the length of the carbon is reduced to 6in. The mechanism of the lamp is very simple, and consists in a rack movement which is regulated by a solenoid in the main circuit, and by another of high resistance, which is placed in shunt to the arc. Both of these are provided with cores built up of bundles of fine wires, so as to avoid heating, and to increase their sensitiveness.

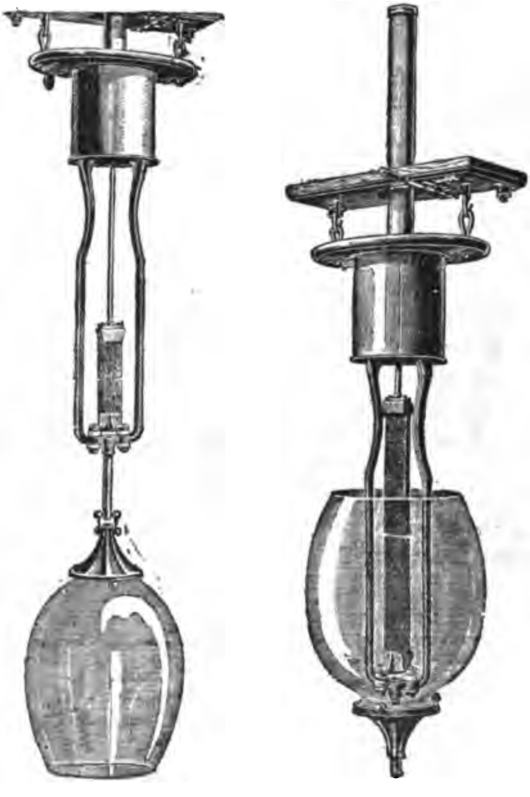


Fig. 66.—Westinghouse Arc Lamps.

There are several accessory devices employed with the system, one of which is a double safety cut-out (*see* Fig. 67). This consists of the usual strips of fusible metal, but, in addition, the points which they span are shunted by a fine German-silver wire. It frequently happens that upon the fusing of the usual safety strip an arc forms at the break, which is apt to travel backward and burn the contacts, and thus ruin the entire device before the arc is broken. By employing the German-silver shunt around these points the fusing of the fusible strip immediately sends the current through the shunt, which at once fuses, breaking into small pieces and forming directly a break of six inches between its terminals—a distance which the arc is incapable of following.

A series of tests have been made on this system, showing its efficiency under various conditions; and for that purpose we give above a table showing the results of a test carried out at the works of the Westinghouse Electric Company in Pittsburgh. These tests were made on a No. 2 30-ampere machine, operating 120 lights. The engine was of the Westinghouse single-acting two-cylinder type, the diameter of the cylinder being $14\frac{1}{2}$in. and the length of stroke 30in. The curves shown in Fig. 68 represent graphically the results given in the table. From these it will be seen that the machine at very light load has a comparatively low efficiency; but beginning with forty lamps up to the full capacity the efficiency rapidly increases until at full load it approximates 87 per cent., and then the energy per lamp required is ·75 horse-power.

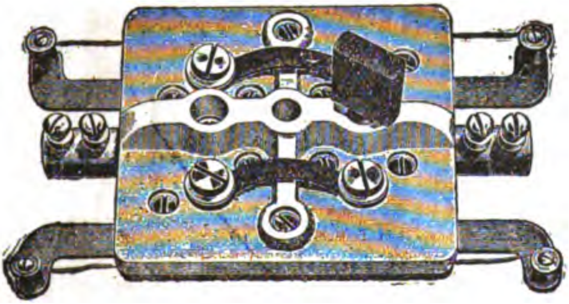


FIG. 67.—Westinghouse "Cut-Out" with Fuse Guard.

In further explanation of the action of this arc-light dynamo, we may add that the regulation for constant current depends primarily upon the fact that the armature is wound with a sufficient number of turns to produce in it a high self-induction, and consequently a lag in the current approaching 90 deg. when short-circuited. According to a well-known law, the current lag, as related to the impressed electromotive force, is reduced by the introduction of resistance into the circuit, and approaches coincidence with the phase of electromotive force as its limit. The magnetisation of the field is so related to that of the armature that when an armature pole is opposite to a field pole, and the magnetising effects are in contrary directions, the resultant magnetisation is reduced to a very small amount. These two elements combine to produce an effective rate of cutting of lines of force approximately proportional to the external resistance in the following way:—When the armature rotates with a high resistance in circuit the lag is small, and the maximum current flows in approximate coincidence with the maximum of electromotive force—that is, when an armature pole is an intermediate position between two field poles. The direction of current is opposite to that in the field coils of the pole it is approaching. In other words, the maximum point in the current phase occurs about 90 deg. in advance of the coincidence of two poles of similar polarity. A reduction of resistance in the work circuit causes a lag in the current phase, so that the maximum point is reached at an instant in time more nearly coincident with the opposition of similar poles; and when the armature coils are short-circuited

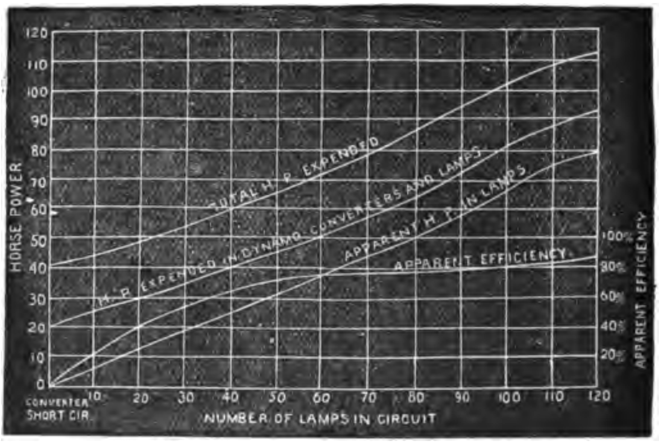


FIG. 68.

and the lag reaches its maximum, the magnetisation of the armature-pole occurs approximately at the time of its passage under a field-pole of opposite polarity. Since the windings of the field and armature are such as to set up approximately equal magnetic potentials in opposite directions, the rate of cutting of lines of force is now reduced to a minimum value sufficient to cause the flow of a normal current through the coils. The current characteristic curve of the machine can be made to approach as nearly to a straight line as can the electromotive force characteristic .of a constant potential dynamo with varying current.

The objects which the Westinghouse Company had in view in this system were—first, to enable them to build larger machines for arc lighting (and thus increase the size of the plant unit) without unduly increasing the potential of the current; and, secondly, to enable them to insulate the lamps themselves from the high-tension mains. It is evident that a constant-current system must necessarily be a series system, if there is to be any variation in the load; and the present system is one in which the converters are connected in series with the line. Constant current in the primary of a converter means that if the windings are as 1 to 1 the current in the secondary is absolutely limited to a value a little below that of the primary current; or, if the windings are as 1 to 3, for instance, then the current in the secondary is limited to slightly less than one-third the primary current. This limitation of the strength of current, combined, as it necessarily is, with a very rapid rise of volts in the secondary if the current falls in consequence of an increase of resistance in the secondary circuit, is precisely what is wanted to ensure stability and consequent absence of flickering in arc lighting; resistance coils such as are required in all cases when arc lamps are run on constant

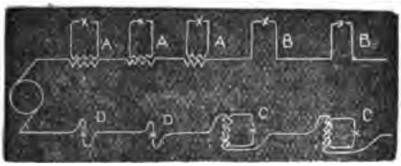


FIG. 69.—10-Ampere Circuit.

potential circuits being, of course, dispensed with. The system is intended more especially for street lighting; but in America private users are also largely supplied by it. When the number of lamps required on a single circuit does not exceed 60, a current of 10 amperes is employed, in which case the converters can be dispensed with altogether in the case of street lamps, if no objection is made to their being in connection with the high-tension mains. In towns and cities where this system has been adopted, private users have also been allowed to have lamps supplied direct without the use of converters, if they wish to avoid the cost of the converter, and accept the risk as regards the high tension.

Fig. 69 is a diagram of a 10-ampere circuit. A A A represent private consumers' lamps supplied with the use of converters. B B represent private consumers who accept the risk of the high-tension mains coming into their premises. C C represent street lamps with converters, and D D street lamps connected directly in series with high-tension mains. The larger machines at present constructed have capacities of 120 and 240 lights respectively, and employ a current of 30 amperes, the larger of the two machines having two independent circuits. This current is much too large for street lamps, so that the facility of connecting lamps directly in series with the mains is practically lost in the case of the larger machines.

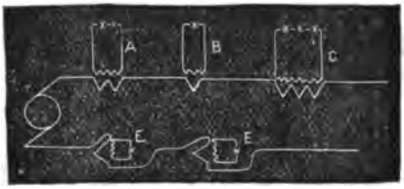


FIG. 70.—30-Ampere Circuit.

Fig. 70 is a diagram of a 30-ampere circuit. A represents two lights, B one light, and C three lights, run from converters for private consumers. E E represent street lamps also run from converters.

The exciting magnets, and also the external appearance of these constant-current machines, are very similar to those of the Westinghouse constant potential alternators, the difference being, as we have seen, entirely in the construction of the armature, which is provided with large overlapping teeth, slightly wider than the gaps between the field poles, so that the edge of one tooth comes under a magnet pole just before another has entirely left. The teeth are equal in number to the field poles, and each tooth carries a constituent coil of the armature winding. No regulating apparatus whatever is employed to keep the current constant, the machine being so designed that the magnetic flux through the armature, and consequently the E.M.F. generated is practically proportional to the impedance of the circuit. Although the action of the machine has been referred to above, the following description, with the aid of the sketches Figs. 71, 72, and 73, may give a further clearer insight into the way in which self-regulation is secured. The proportion of the winding of the armature to that of the field coils is such that at the moment of maximum current the ampere turns of the armature coils are approximately equal to those of the field coils, and consequently if the armature current reaches its maximum at a moment when the teeth approach coincidence with the poles, the magnetic flux will be very small, and the E.M.F. generated only just sufficient to send a harmless current through the armature when short-circuited. In Fig. 71 the armature teeth are shown in the position midway between the field poles, and, as is obvious, the induced E.M.F. will be at a maximum in this position. If no current is allowed to flow, the field coils produce a large magnetic flux, and a high E.M.F. is generated, which in the machines as constructed may reach 10,000 volts or so. It is therefore advisable for safety

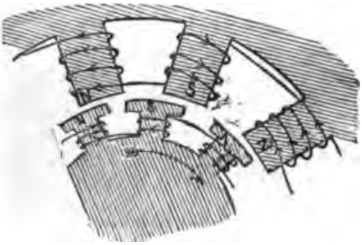


FIG. 71.

to short-circuit the armature when running without load, and an automatic arrangement, as above mentioned, is provided on each machine to effect this. If, now, the armature circuit is closed with a moderate resistance in circuit the lagging of the current behind the impressed E.M.F. causes the armature teeth to have made an approach towards coincidence with the magnet poles (*see* Fig. 72) at the time when the current in the armature coils has reached its maximum value. This approach towards coincidence considerably increases the self-induction of the armature by improving the magnetic circuit, which has the effect of making the lag much greater than it would have been had the self-induction of the armature remained constant; so that by a cumulative process the lag due to an increase of current in the armature winding is considerably magnified. The approach towards coincidence between the armature teeth and the magnet coils at the moment of maximum current also has the effect of directly cutting down the E.M.F. by bringing the magnetising force of the armature winding into more direct opposition with that of the field coils, and thus reducing the magnetic flux through the armature, until when coincidence is practically reached (*see* Fig. 73)—as it is when the armature is short-circuited—the armature and field windings oppose each other on very nearly equal terms, and the magnetic flux is only sufficient to cause a slightly increased current in the armature.

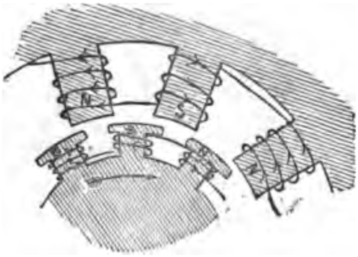


FIG. 72.

In the machines as constructed, if the resistance inserted consists of a load of converters in series, with arc lamps in their secondaries, the lag due to the current flowing in the armature will be such that the magnetic flux due to the resultant of the magnetising forces of the field and armature coils will be of the value necessary to produce the normal volts for that particular load; and the Westinghouse Company claim to have succeeded in turning out machines so sensitive that a practically negligible variation in the current causes a variation of E.M.F. in the external circuit from nil when the armature is short-circuited up to 2,000 or 3,000 volts when loaded up with converters and arc lamps. It is stated that the full load can be suddenly thrown on or off without doing any damage to the machine, the current remaining practically steady during either operation. The 240-light machines, as has already been stated, are double circuit machines, and are generally employed in large towns and cities for street lighting, where there is not much variation in the load, when it is found that the interference between the two circuits is not noticeable. It is, of course, impossible that the two circuits should regulate independently.

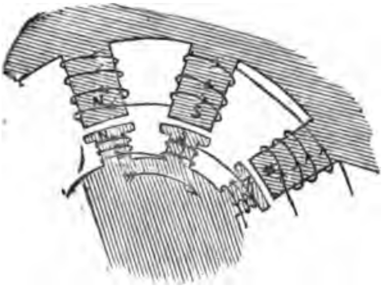


FIG. 73.

The transformer employed is a closed circuit one. Lamps are extinguished by short-circuiting the *secondary* coil, a proceeding which causes very little waste of energy, owing to the low value reached by the induction in the iron and the small resistance of the copper circuit. The results of the secondary being on open circuit would be to cause heating of the core, due to the high value reached by the induction, and to choke the primary. To insure perfect insulation between the primary and secondary coils, they are wound on separate bobbins, with a considerable space between the two. The slight loss of efficiency resulting from this arrangement is said to be of relatively small importance in a series arc system. The space between the coils and the cover is filled up with wood blocks and insulating compound, the object of the latter being to keep out damp.

With regard to the arc lamp, the only point which has not been already described is the addition of a small reflector around the upper carbon to throw the rays from the lower carbon crater in a useful direction.

§ 18. **The Lowrie-Hall System.**—The various elements in the transformer system of the House-to-House Electric Light Supply Company have been brought to their present perfection by the inventive skill of Mr. W. Lowrie and Mr. C. J. Hall. The alternator built by Messrs. Elwell-Parker, of Wolverhampton, is of a somewhat similar type to the alternator of Messrs. Zipernowsky, Déri, and Bláthy, employed in the Ganz system. In this machine the stationary portion is the armature in which the current is generated, and the revolving portion constitutes the field magnets. Fig. 74 shows the general external appearance of the 100-unit size machine, having a safe out-put of 100,000 watts, or 130 horse-power. The circular iron frame is composed of thin sheets of charcoal iron, ring-shaped, insulated from each other by paper, and bolted together. This armature ring is parted on the central horizontal line so that the upper part can be lifted off to insert or remove the field magnets. This ring-frame is carried on the cast-iron frame work of the machine, but is insulated from it. On the inner cylindrical surface of this ring-shaped iron core are fixed the armature coils. These coils are formed of copper tape, each wound on a former so as to form a coil of flat or link shape, and yet slightly curved so as to fit closely to the inner surface of the armature core. The edges of the tape winding are thus exposed. The centre of the flat coil is occupied by a piece of insulating material. These flat coils are placed close together upon the cylindrical inner surface of the divided iron armature ring so that the axis of each coil is radial to the ring, and the coils are secured in their places by strips of wood screwed to the cheeks and extended over the ends of the coils outside the line of travel of the magnets.

These armature coils are then joined up in series, and the terminal wires brought to insulated terminals on a sheet of ebonite contained in a lock-up box. There are twenty-eight armature coils thus joined in series, each coil producing about 70 volts, or 2,000 in all.

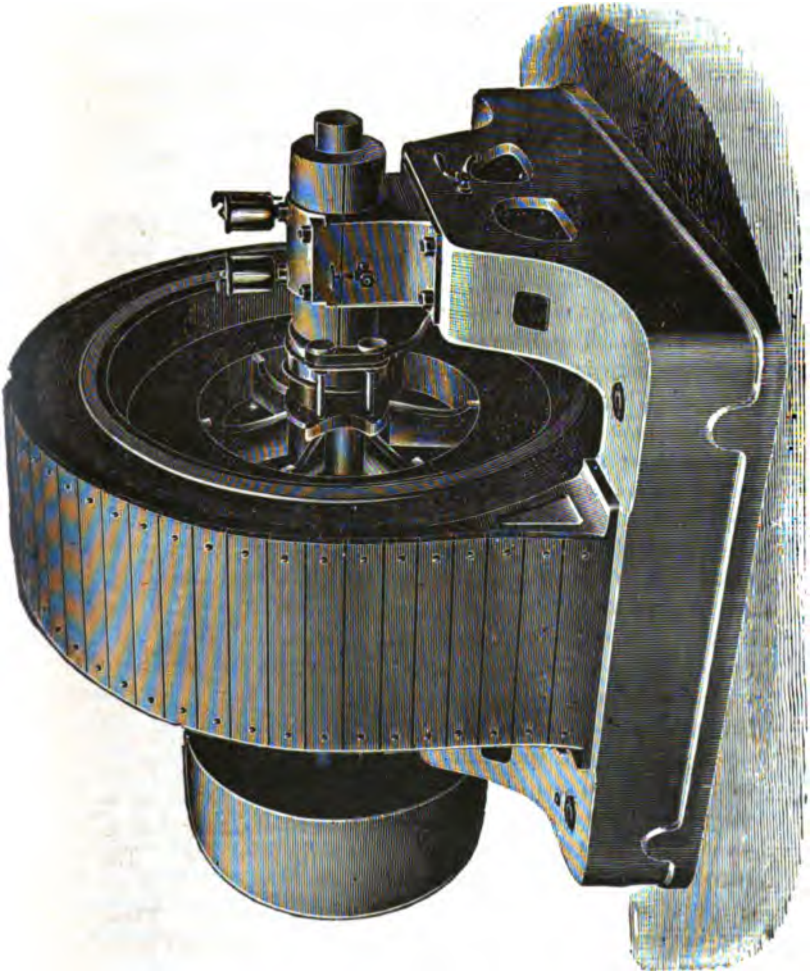


Fig. 74.—100-Unit Lowrie-Hall-Parker Alternator.

The armature coils can be easily individually removed for examination or for repair. The field magnet or revolving portion of the machine consists of a solid soft wrought-iron ring, with wrought-iron radial pole pieces securely attached thereto; and these pole pieces are of solid wrought iron.

The exciting coils are wound on shells, which are slipped on to these pole pieces, and secured by bolts from being displaced by centrifugal action. There are twenty-eight such radial magnetic poles, alternately N. and S. polarity.

The coils of the field magnets are joined up in series, and the terminal wires are brought to two insulated gun-metal rings on the steel shaft of the dynamo.

The current density in both armature coils and field magnet coils is not allowed to exceed 2,000 amperes per square inch of section.

The base plate of the dynamo is of strong box pattern, ribbed and flanged. The frame for supporting the laminated iron armature core is cast separate, and securely bolted to planed facings. The plummer blocks for the bearings are cast separate from the base plate, and secured thereto by bolts and lugs and wrought iron wedge keys. The bearings of the magnet shaft are each 20in. long and fitted with brasses of phosphor bronze. The bottom brass is so arranged that it can be removed without lifting the shaft and yet well secured sideways. The bearings are provided at each end with oil catchers, by which used oil is caught and drained away to a tank in the base plate, from which it can be drawn off and filtered for re-use. The steel shaft carried by these bearings is 6in. in diameter. It carries a cast iron hub to which is secured the wrought iron ring with the magnet poles. The shaft carries two gun-metal rings insulated from each other and from the shaft to which are attached the ends of the field-magnet circuits, and by means of which the exciting current is passed into the field circuit. Each ring is provided with two sets of brushes, each set being ample for collecting the exciting current, and the brushes and their holders are carried by a support from the base plate. Suitable adjustable springs control the pressure of these brushes, and their holders are carried against their contact rings. The shaft carries two pulleys of cast iron—one, the driving pulley, turned with seven grooves for seven 1½in. ropes, and the other turned with four grooves for four ¾in. ropes for driving the exciter dynamo. The exciter is a series-wound machine, with drum armature, running a speed of 800 revolutions per minute. Each alternator has its own exciter, and for the 100-unit alternators the exciters furnish a current of 25 to 28 amperes at 120 volts.

The speed of the alternators is 350 revolutions per minute, giving an alternating current having about 10,000 alternations per minute, or a "frequency" of 83.

The output of each alternator is 50 amperes at 2,000 volts. The over-all height of this alternator is 8ft. 6in., and the weight 10 tons. A separate pair of wires are taken off one coil of the armature for the purpose of regulation of electromotive force in a way to be presently described.

The commercial efficiency of this alternator at full load is stated to be about 85 or 87 per cent. These alternators are also said to work well in parallel. If two alternators driven by separate engines are thrown in parallel and the steam is shut off one engine, it still continues to be taken round by its dynamo acting as a motor and driven by the fellow-dynamo acting as a generator.

Alternators of this type are made in the following sizes:—

Safe output in kilowatts.	Load in 60-watt lamps.	Revolutions per minute.	Revolutions of exciter per minute.
30	500	600	1,000
45	750	550	1,000
60	1,000	500	1,000
90	1,500	400	800
120	2,000	350	700
150	2,500	300	600
200	3,300	250	500

All these machines are arranged to give an alternating current having 10,000 to 12,000 reversals of current per minute, and electromotive force of 1,000, 2,000, or 3,000 volts, as required.

§ 19. Lowrie-Hall Transformers.—The transformers are of the closed magnetic-circuit core type. Two iron cores are formed of piles of thin iron plates (*see* Fig. 75), each plate being separated by thin paper from the next. On each of these cores is wound a primary and a secondary coil one over the other, part of the iron core projecting beyond the coils at both ends. The two coil-covered cores are then placed side by side, and the plates of the cores projecting beyond the coils are turned over alternately, each pair of plates forming a closed magnetic circuit. The whole of the plates are then clamped tightly together at both ends to ensure good magnetic contact. The completed converter shown in Fig. 76 thus seems to form a closed laminated iron ring of rectangular shape, and having a primary and secondary coil wound on each side of the ring. The transformers are placed in iron converter cases (Fig. 77). The pairs of primary and secondary coils are respectively joined up in series, and the terminals brought to insulated terminals outside the case. The usual primary and secondary double-pole fuses are placed in porcelain boxes on the case. The converter cases have lugs and rings so as to suspend or fix them in place. These trans-

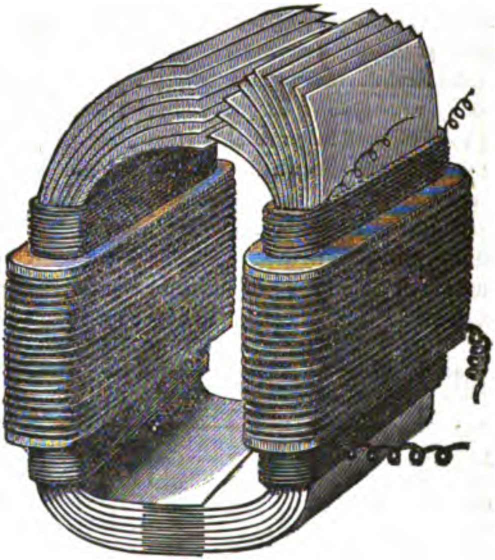


FIG. 75.—Diagram showing Method of building up the Lowrie-Hall Transformer.

formers are said to take about ·02 ampere-current in the primary when on open secondary circuit. The various sizes used

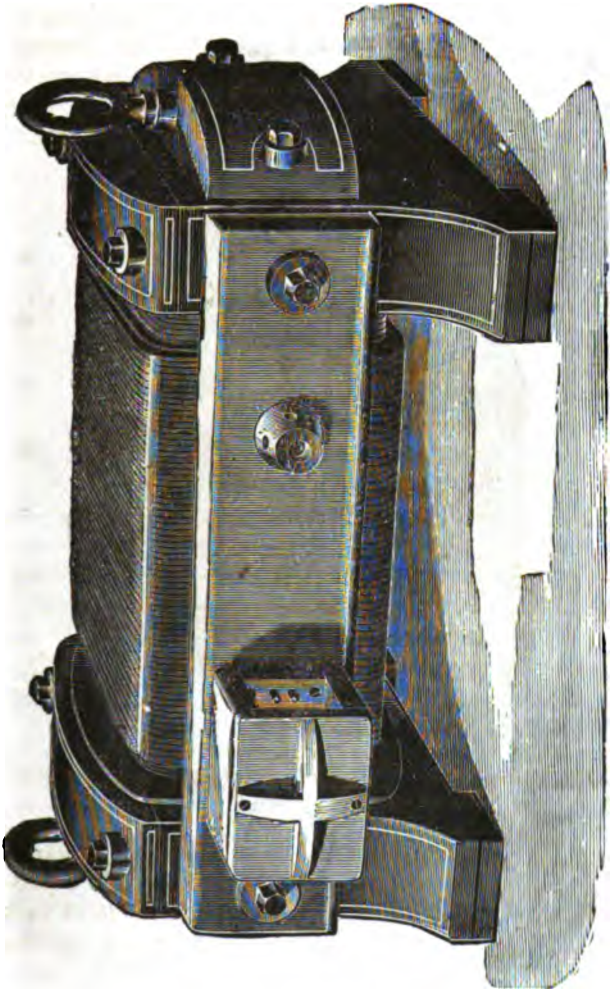


FIG. 76.—Lowrie-Hall Transformer.

are for out-puts of 1, 2, 4, 6, 8, 10, 16, 20, 30, 40 E.H.P., and are wound to convert from 2,000, 1,500, and 1,000 volts to 100 or 50 volts.

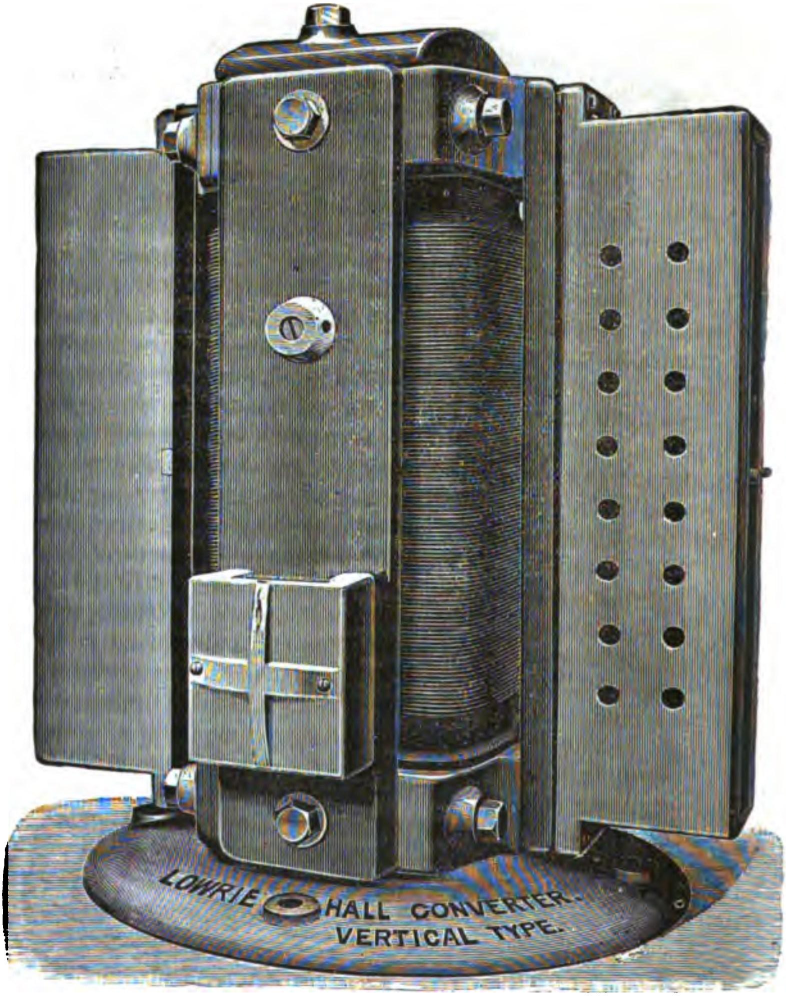


FIG. 77.—Lowrie-Hall Transformer.

§ 20. House-to-House Central Station at West Brompton.—The House-to-House Electric Light Supply Company have established at West Brompton, in London, a very complete transformer station on the Lowrie-Hall system.

The site of the station is a plot of land, 470ft. long by 60ft. wide, adjoining the Metropolitan District Railway. On this site has been erected a central station capable of supplying current to about 48,000 50-volt 10-candle-power incandescent lamps. The general appearance of a small portion of this station is shown in Fig. 78, and the whole station comprises dynamo and engine room, boiler house, testing-rooms, offices, stores, drawing and engineer's offices, water tank, coal stores, &c.

The station when completed is intended to have 12 unit plants, each consisting of an engine, boiler, dynamo, and exciter, and capable of giving an electrical out-put of 100,000 watts. At the present time (1890) three such unit plants are actually in place, and the remainder will be added as required. The present supply is to about 16,000 eight candle-power 50-volt lamps, some 10,000 of which are at full load, burning at one time. The supply is to numerous private houses, flats, shops, St. Jude's Church, and other public buildings.

Each alternator is driven by a 200 horse-power horizontal coupled compound engine, by John Fowler and Co., of Leeds. The high-pressure cylinder is 15in. in diameter, the low-pressure 25in. in diameter; the stroke is 30in.; and the initial steam-pressure is 130lb. per square inch. The speed is 88 revolutions per minute. The cylinders are steam-jacketed. Between the high-pressure and low-pressure cylinder is suspended a massive flywheel, 14ft. in diameter, grooved for seven 1¾in. ropes. The engines are governed by Hartnell's governor, which is driven from the shaft by cotton ropes, and controls the engine by acting direct on the expansion valves of the high and low-pressure cylinders, giving a range of cut-off in the high-pressure cylinder from 1 to 60 per cent. of the stroke, and governs the engine speed to within 2 per cent. The approximate weight of each engine is 24 tons. Each engine drives its associated dynamo and alternator by means of seven cotton ropes.

Efficient means for tightening the driving ropes are provided, consisting of two cast-iron rails of heavy section, fitted at one end of each with forcing screws; provided with holding-down

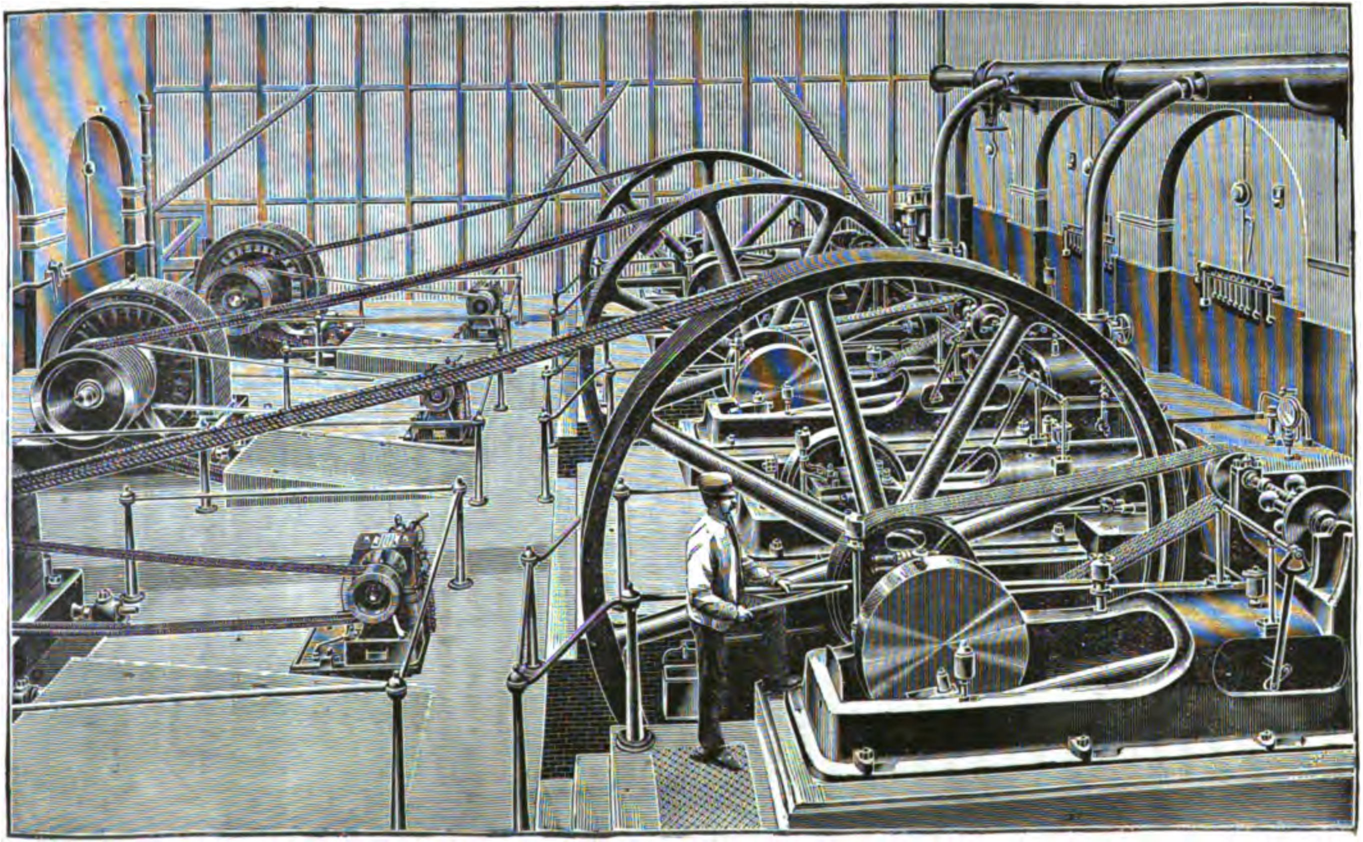


FIG. 78.—View of a part of the House-to-House Central Station, West Brompton. Main Engines and Alternators.

bolts for the dynamo, the nuts of which are of rectangular form and sliding in grooves formed in the rails, the bolts being thus applied from above are removable without lifting the dynamo. The two rails are securely tied together with cast-iron distance pieces. Similar arrangements are supplied for the exciter. The foundations of all the engines and dynamos below ground are built of hard gault bricks, set in Portland cement, on a continuous slab of Portland concrete. The engine floor is raised three steps above the general floor line, and each engine base set up 14in. on a blue Staffordshire brick pedestal for conveniently reaching all the parts, and at the same time to secure natural drainage to the driving-wheel races. The floor on the raised platform is paved with blue Staffordshire bricks. All round the dynamos and exciters is a highly-insulated platform of crossed floor boards set on joists, with bitumen between the two sets of boards and linoleum laid throughout. This platform is also raised 6in. above the general floor line.

The boilers are the well-known Babcock and Wilcox water tube boilers with steam drum, capable of evaporating easily 5,500lb. of water per hour, and requiring not more than 1lb. best Welsh coal per 10½lb. water evaporated. Daily working pressure 150 (one hundred and fifty) lb. per square inch. The details of each boiler are as follows :—

	Feet.	Inches.
Number of tubes in each boiler, 81	—	—
Length of tubes	18	—
Diameter of tubes	—	4
Length of steam drum	23	—
Diameter of steam drum	4	—
Length of mud drum	5	6
Diameter of mud drum	1	6
Number of sections or slabs in each boiler	9	—
Total length of boiler	23	—
,, height ,, ...	14	8
,, breadth of all three boilers together	22	9
Heating surface on each boiler	1,790 sq. ft.	
Grate area in each boiler	33½ sq. ft.	

All joints in tubes, headers, hand-holes, &c., are metallic, no indiarubber, asbestos, or such like material being used. The entire boiler is suspended from a gallows or supporting frame, quite independent of the brickwork, thus allowing free expansion and contraction, and the removal, if necessary, of the brickwork, without disturbing the set of the boiler or connections. The steam drum, where exposed to radiation, is covered 2in. deep with non-conductor. The chimney shaft is common to all three boilers. Its dimensions are:—

	Feet.		Inches.	
Height from base-plate.........	100	...	0	above ground.
Inside diameter	5	...	6	
Outside diameter at base	11	...	0	

These dimensions are sufficient for a battery of six boilers, the intention being to erect another shaft for the second six boilers. Below ground the chimney rests on a slab of concrete 20ft. square by 6ft. thick on the red London gravel.

The boilers are connected with copper connecting pipes to a 15-inch steel main pipe (this latter being of sufficient size to supply steam from 12 boilers to 12 sets of plant), carried on brackets fixed on the side of the wall, and each engine is again connected thereto by a copper bend pipe; the connections, both to engines and boilers, are arranged so that their spring or flexibility will allow for expansion of the main steam pipe, thus dispensing with any expansion joints. The condensed water from the pipe is collected in a receiver for use in the works and for the meters. The joints of this pipe are made with rings of copper tube covered with asbestos, fitting into a small spigot and faucet formed in the flanges. The exhaust pipe, 27-inch diameter, is also arranged to be common to all engines. It is of steel, similar to the steam pipe; the connection from the engines and to the heaters being of copper, arranged to take the expansion of the main pipe.

After passing through the heaters or the by-pass provided, the exhaust steam passes into the chimney, the drain from this pipe passing into a well under the water level. The drain pipes from the engines are also all taken to a main drain pipe common to all engines and carried to this well and under water. This well is automatically drained of surplus water and prevents steam from being blown direct into the sewers.

The high-pressure leads from the alternators are brought to a switch room, and all connections, governing, and changes are effected in this room. As at present (1890) arranged, each dynamo works on to a single and separate primary main. There are already about 25 miles of such primary main laid in the streets. The three pairs of leads from the three alternators and the ends of the three pairs of primary street mains are all brought to a switch-board, and by a simple 4-plug switch any dynamo can be put into any main. The leads from each dynamo have their own double-pole safety fuses, ammeter and voltmeter. There is also a double set of synchronising transformers for putting any pair of dynamos in parallel, as described in connection with the Leghorn Central Station (*see* § 9).

The mode in which this cross-connection of any dynamo to any main is made is very simple and practical.

Four straight terminals are mounted upon bosses of earthenware bolted to a slab of slate. The front earthenware bosses are deeper than the projection of the terminals from the face of the slate, to protect the terminals from dust, dirt, and the like, and to prevent accidental contact. The entrance orifices of these front bosses are funnel shaped, in order to guide the plugs to their respective seats in or upon the terminals. The back ends of the latter protrude through the back earthen ware bosses, to which they are secured, and the terminals are formed to receive and bind the circuit conductors. This arrangement of four terminals upon their base is termed a terminal base. Upon a similar but smaller base of non-conducting material are also secured four plugs corresponding in position to the aforesaid terminals. In the centre is a wooden or other insulated handle; and a stop is fixed to limit the insertion of the plugs within the terminals. A strip of copper electrically connects each pair of plugs; and the base, with its handle and four plugs, is called a plug base. The combined four-terminal base and four-plug base is called a unit switch block.

The arrangement of the plugs, and that of their corresponding terminals, is that of a rectangle, nearly square in dimensions. This is to prevent the plug base being inserted wrongly in the terminal base, to make vertical connections (for example) instead of horizontal ones. The smoothing-iron form of the handle also serves to indicate the position in which the plug base should be held in switching, so that by the rectangular form and arrangement of the circuits it is impossible to plug the wrong terminals in a unit switch block. The terminals are made in the form of a split tube, to make spring contact upon the exterior surface of the solid plugs.

The requisite number of switch blocks are mounted upon a suitable support, in the form of a square. Upon one side of the square we connect each of the unit switch blocks to a generator, and upon a horizontal line with each of these a similar switch is placed, one for each, and connected to the working of the outer circuits.

In the respective circuits named are placed safety fuses, and the arrangement is such that one pole of a dynamo machine is connected to one terminal of a unit switch block, while the other pole is connected to the diagonally placed terminal of the same switch block. Similarly, each pole of the outer circuit switches is electrically connected to the remaining two terminals of the same block.

Provision is made by grooves at the back of each unit switch block to extend all the electrical connections to the adjoining unit blocks in the same symmetrical manner. For example, when four unit blocks are combined together as a square, with connections from two dynamos on one side, and connections to two working circuits at right angles thereto, the whole of the current from the two generators can be conducted into one of the working circuits; or, the current from one machine led into one circuit, while the other machine is supplying the other circuit; or, one circuit is fed by both machines, while the other circuit draws its supply from one machine only; or, finally, both circuits may be fed by both generators, according to the number and arrangement of the plug bases engaged with their respective terminal bases. Thus, any number of generators and circuits can be electrically connected by adding the requisite number of unit switch blocks in the manner indicated.

The next important element in the system is the self-regulating arrangement, by means of which a constant electromotive force of 2,000 volts is kept at the terminals of each dynamo. As the loss of volts in the primary mains between full load and lightest load is only 2½ per cent., no adjustment is made for varying current in the main, but the terminal pressure difference is kept constant at the machine.

This is effected by regulating the exciter current by shunting more or less of the field current of the series-wound exciters. From the terminals of one single coil of the armature of the dynamo is taken off a pair of wires, and the 75 volts of this coil is reduced by a small transformer to 50 volts. The current from the secondary of this small transformer is passed through two horizontal fine wires, like a Cardew voltmeter, and the greater or less expansion of these wires, as the E.M.F. of this coil of the armature varies, causes a greater or less sag of these wires. This expansion is then made to effect the regulation as follows:—

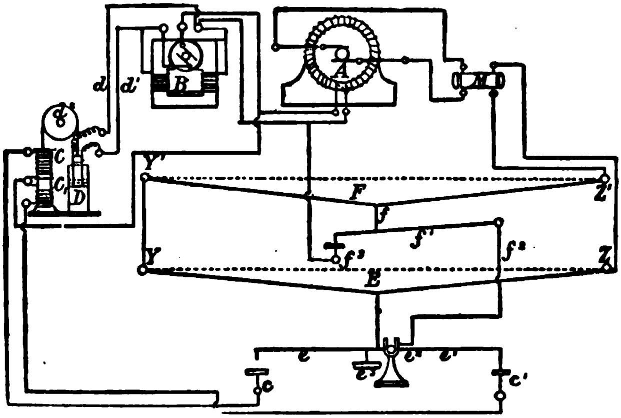


FIG. 79.—Diagram of Connections for Lowrie-Hall Pressure Regulator.

Across the terminals of the above-mentioned transformer, M, are the two fine wires, E and F (*see* Fig. 79), supported between the fixed points, Z, Y, and Z^1, Y^1, whose normal positions when cold are shown by the dotted lines, the two wires being in series with one another, and connected by the wire Y, Y^1. The field-magnets of the alternator, A, are excited by the exciter, B. Across the fields of this exciter a shunt of varying resistance is placed, connected by the wires, *d*, d^1; this shunt resistance is formed by two metal plates dipping in the solution in the electrolytic cell D, and its resistance is altered by the raising and lowering of the plates into the solution, which is accomplished automatically by the passage of a current through either one of two solenoids or coils which pull up or down an iron core inside the coils; the top coil, C, lowers them, and the bottom coil, C_1, raises them, by the attraction of this movable iron core inside the coils.

This core is attached to the plates by a cord passing over a pulley d^2. To the centre of the wire E a cord is attached, the other end of which is fixed to the arm e of the rocking arm e, e^1; this arm is pivoted at e^2 on a fixed support. If the electromotive force of the dynamo rises too high, the sag becomes greater, and the arm e is pulled down by the weight e^3, and so makes contact on the table c; if, however, the electromotive force falls, the wire pulls the arm c up, so causing the other arm, e^1, to make contact with the table c^1. To the centre of the wire F the cord f is attached, which raises or lowers the arm f^1, pivoted at its end, off or on to the table f^3. This table f^3 is connected to one pole of the exciter, and the pivot of the arm f^1 is connected by the wire f^2 to the pivot of the rocking arm e^2; the table c is connected to the top coil C, and the table c^1 to the bottom coil C^1, the other ends of these two coils being jointly connected to the other pole of the exciter. If now the electromotive force of the dynamo rises too high, the arm e falls, so making contact with the table c; the electromotive force of the exciter is therefore right across the coil C, one side being in metallic connection, and the other being connected through the table f^3, up the arm f^1, through the wire f^2, to arm e, so passing through the table c, connected with the coil C. This coil coming into action pulls the core up and so lowers the plates into the solution, which therefore lowers the resistance of the shunt, so causing less current to pass round the fields of the exciter, and consequently weakening the field of the dynamo A, so lowering its electromotive force. These coils, C, C_1, it should be mentioned, are wound with fine wire and are of high resistance, so that their connection across the exciter has no effect upon the dynamo A. If, however, the electromotive force is too low, the arm e^1 touches the table c^1, so shunting the current through the coil C_1, which, coming into action, raises the plates out of the solution, and consequently the resistance of the shunt, so that more current passes from the exciter round the fields of the dynamo A, whose electromotive force therefore rises. The arm f^1 is put in to cut out the action of the regulator in the event of the wire E breaking, for that wire by breaking would stop the passage of the current through the wire F, so making the latter contract and pull up the arm f^1, so breaking its connection with the table f^3. If no provision is made for this accident, the arm *e*, by making permanent contact with the table *c*, would lower the electromotive force of the dynamo as far as the shunt would allow. In the shunt resistance, the two plates, which are fixed to an insulating piece, dip into the solution contained in the glass cell. The plates are supported by two chains, which pass over the two ebonite wheels; these chains make connection with the plates and terminate at two terminals, having sufficient slack to allow the wheels to turn their maximum distance either way. On a smaller pulley a chain is fixed, supporting the iron core, which moves up or down in the coils; the speed of the motion of the plates is increased or decreased by the ratio of the diameters of the pulleys. The coils are wound upon a brass tube, which is filled with glycerine to act as a dash-pot, the core acting as a plunger itself. The plates in the shunt resistance cell should be changed periodically to reverse the chemical action of the current upon them. In the actual instrument thus designed to utilise the sag of a wire, the wires are stretched in a brass tube, in the centre of which is a containing box; at each end of the tube is a disc or insulation; on one of which are two movable brass strips to tighten the wires by the action of the thumbscrews. These are used to adjust the instrument; on each of these strips is a terminal, so that they make electrical connection to the wires. At the other end of the tube a brass piece is fixed, on to which both wires are screwed. The rocking arm is jewelled in both movements. The use of the guiding arm is to bring the centre pin on to the bridge, so that when the current ceases the wire is free to contract. All the contacts are made of platinum, and the connections to the tables are made in the terminals underneath; these tables are all adjustable from below, so that their height may be altered without allowing cold air to get into the tube whilst the current is on. The use of the other arm as a cut-out has already been described. The use of one wire is that of a cut-out as before described. It will be seen that another method of rendering the instrument still more sensitive or the reverse, is by moving the attachment of the cord on the rocking arm nearer to or farther from the pivot.

The external appearance of this regulator is shown in Fig. 80.

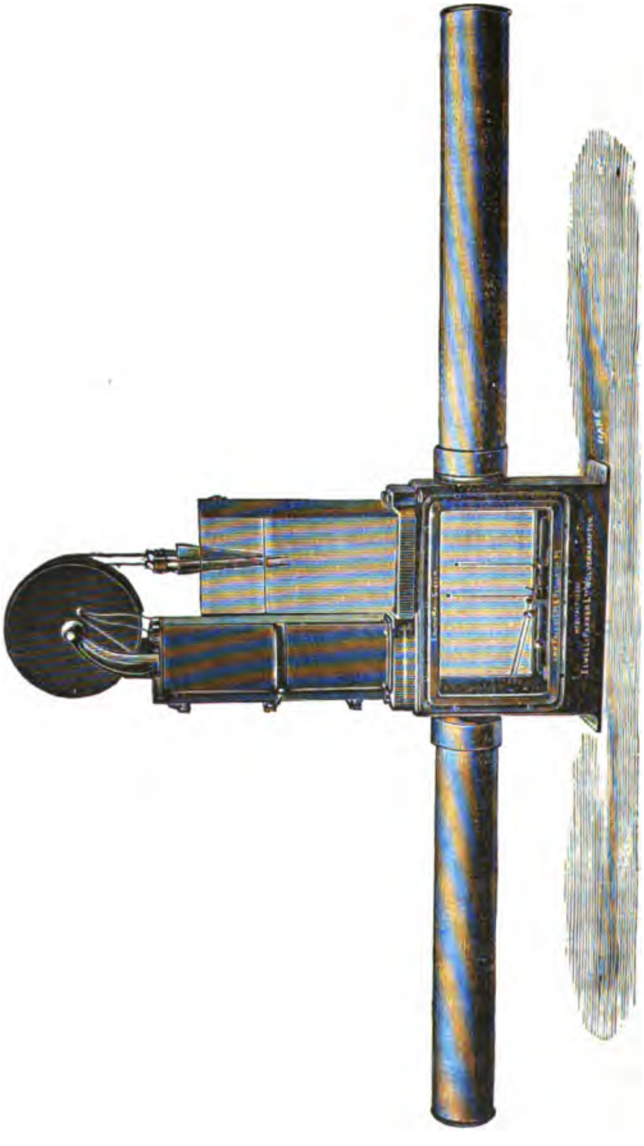


Fig. 80.—Lowrie-Hall Electromotive Force Regulator.

§ 21. **Lowrie-Hall Distribution System.**—This distribution system is an underground system. Cast iron pipes are laid in the streets, having junction boxes every forty feet, and surface boxes at the street corners. Into these pipes are drawn stranded copper cable heavily insulated with vulcanized india-rubber covering, and the joints are covered with rubber insulation vulcanized *in situ*, after making the joint, by a small portable heater. The positive and negative mains are run in the same iron pipe. Fresh cables can be drawn in as required. At the junction boxes distributing mains are taken off to the transformers. These are placed in iron boxes or in the cellars or areas of the houses. Each house may be served by a single transformer, or one or two transformers may be banked to serve a group of houses or shops off their common secondaries. This underground system has, it is said, given great satisfaction in use. A simple method is adopted to roughly test the leakage from either primary main. A vacuum tube, having one platinum wire terminal put to earth, has its other platinum wire terminal connected to one or other of the primary mains. As long as the insulation of the primary main is good, this vacuum tube shows a glow-light in it; but if a bad fault occurs on the main, this glow-light no longer is seen.

In connection with the Lowrie-Hall system should be mentioned an ingenious meter by which the record of the lamp-hours is kept. The alternating current from the secondary coil of the transformer is made to pass on its way to the lamps through a small secondary battery and a copper voltameter consisting of a pair of copper plates suspended in a solution of sulphate of copper. The alternating current which illuminates the lamps has in itself no ability to cause a deposition of copper upon the plates, but when lamps are turned on the secondary battery sends a current through the copper voltameter which is exactly proportional in strength to the number of lamps turned on, and to the current-using capacity of each. Hence the secondary battery causes a continuous current to flow through the voltameter, increasing the weight of one plate and diminishing that of the other to a degree which is exactly proportional to the quantity of alternating current which has passed in that time. What is measured is not the current illuminating the lamps, but a much smaller continuous current, which is, however, at every instant exactly proportional to the alternating current. Hence the loss in weight of one copper plate is exactly proportional to the quantity of the alternating current which has traversed the lamps. A monthly removal of the plates for weighing, and a renewal of the charge of the secondary battery, suffices to enable a charge to the consumer to be made according to his consumption.

§ 22. **Madrid Central Station.** — The House-to-House Company have designed a model central station on this Lowrie-Hall system. Each engine, boiler, alternator, and exciter forms a separate and complete plant, and a series of these unit plants are placed side by side, the unit being approximately for about one-twelfth part of the capacity of the full station. The same Company have established on the Lowrie-Hall system a very complete transformer station, after this model, at Madrid. This station was opened in October, 1890. The works are situated close to the railway station, Las Delicias. The engine and dynamo-room and boiler-house are each about 132 feet long and 60 feet in width, extending parallel to each other. There are at present installed six unit plants, each consisting of engine, boiler, and dynamo, together with the necessary offices and workshops. The present capacity of the station is for 24,000 10-candle lamps. In its plant and arrangement the station otherwise resembles the Brompton station, already described.

§ 23. **Transformer Stations of the Metropolitan Electric Supply Company.**—The Metropolitan Electric Supply Company have established at Manchester-square, London, as part of their system, a transformer station, in which Elwell-Parker alternators and transformers are employed. Like their Sardinia-street station, Manchester-square is an alternate transformer station, supplying distributed transformers placed on customers' premises by means of an underground system of primary conductors. The site on which the station stands was formerly a stable, and the first sod was turned on August 12, 1889, in the commencement of the station which has been erected in that place. The station will be capable, when in full operation, of an electrical output of a million watts. Hence it will be able to supply an actual demand of 30,000 30-watt lamps, or 50,000 such lamps wired. The station buildings are substantial brick buildings, which have been laid out with great skill to economise to the utmost the space at disposal.

The dynamo room (Fig. 81) contains a set of ten generating units, each composed of a 200 horse-power Willans triple expansion engine, working under a pressure of 200lb. of steam, combined on the same bed-plate with, and driving direct an Elwell-Parker alternator, having an output of 100 kilowatts.

The engines work at a speed of 355 revolutions per minute, and require 200lb. pressure of steam. The Elwell-Parker dynamo coupled to it has already been described in detail.

The dynamos at Manchester-square have 36 magnet poles on the revolving field magnets and 36 coils in the stationary armature, and, accordingly, there are about 12,000 alternations per minute in the resulting current, or a frequency of 100. The exciting current employed is a current of 28 to 34 amperes at a pressure of 100 volts. Each dynamo-bearing is provided with arrangements for circulating cold water through the hollow bearings in case of heating.

These alternators furnish a current of 100 amperes at full load, under a pressure of 1,000 volts. To excite this battery of 10 alternators there are four exciters by Elwell-Parker, which are the ordinary shunt machines, each driven by a triple-expansion direct-coupled 60 horse-power Willans engine at a speed of 475 per minute. Two of these exciters are equal to doing the whole work of exciting the 10 alternators, and the fields of the alternators are, as usual, joined in parallel across the poles of the alternators.

The arrangements for preventing the transmission of vibration from these engines and dynamos to the ground around are very perfect. In preparing the foundations for each engine and dynamo, the ground was first excavated for a depth of 10 or 12ft., and a pit formed (*see* Fig. 82) in which was made a solid floor of concrete, and the sides built up. On this floor of concrete was laid a thick sheet of felt, and then one of lead, and on this was built up

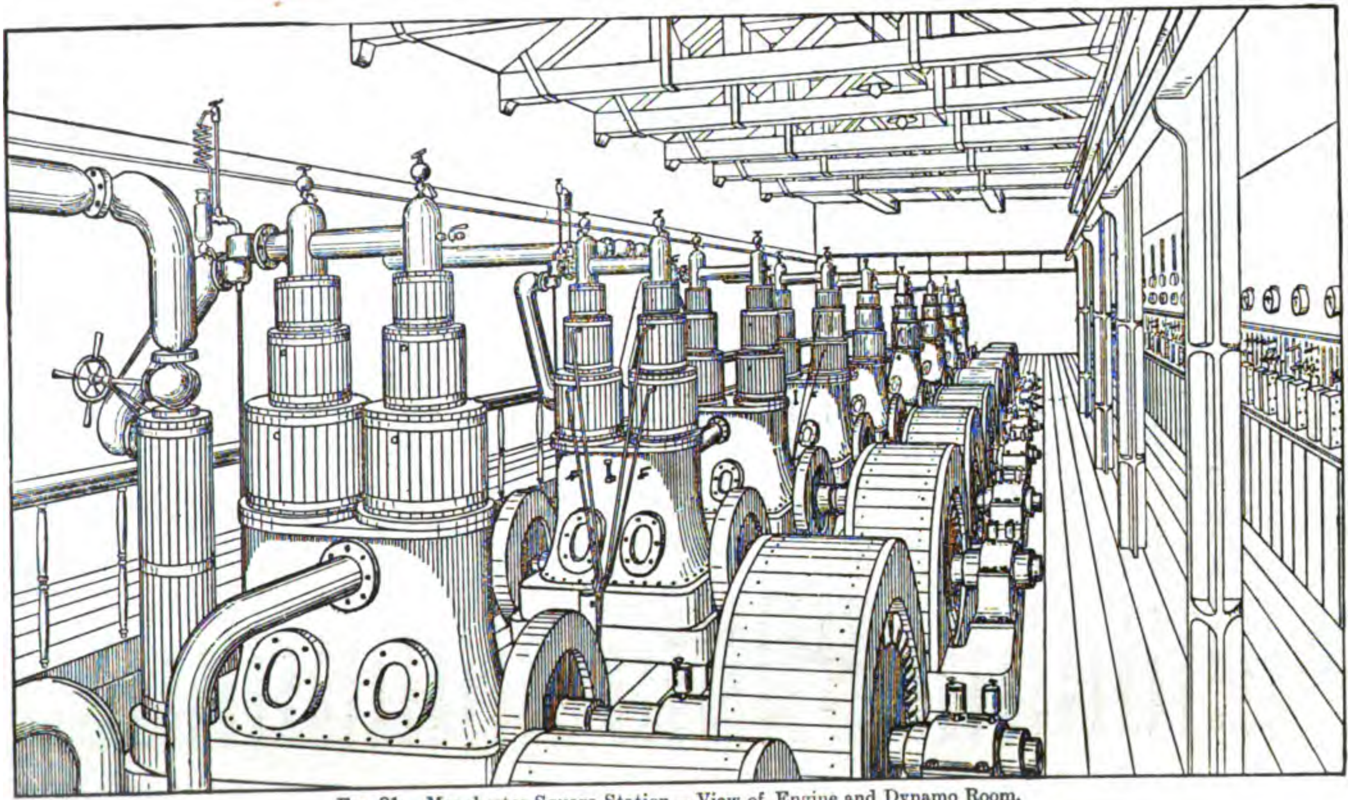


FIG. 81.—Manchester Square Station.— View of Engine and Dynamo Room.

a block or table of brick. On this table the bed-plate of the engine and dynamo was fixed and bolted. The object of this arrangement was to quench all vibration and prevent the communication of thump to the walls of the building and to the ground around. Entering the boiler-house (*see* Figs. 83 and 84) we find a battery of nine Babcock and Wilcox tubular boilers, each capable of evaporating 6,000lb. of water per hour. The consumption of all the engines when at full load will be 40,000lb. of water per hour. The arrangement, due to Mr. Rosenthal, by which large steam pipes are avoided is worth notice. Over each pair of boilers is a wide pipe or drum, and from each drum proceed steam pipes to two engines. All the drums are connected by equalising pipes, and as a result there is no steam pipe other than these drums which is larger than five inches in diameter, and the difficulties with large bends and joints thus avoided. The steam stop-valves which shut off each boiler are made with an outside screw thread, and a gunmetal female screw having a longitudinal slot through which oil can be squirted through the thread to prevent sticking. Each boiler has two feeds, one hot and one cold; so that if the hot feed fails from any cause the cold feed can be supplied. In blowing off the hot water from the boiler there is an arrangement by which cold water is mixed with the hot, so as to reduce it below a temperature of 212deg. when it enters the drains, or else the result of "blowing off" would be to fill all the drains of the surrounding neighbourhood with steam. A water tank

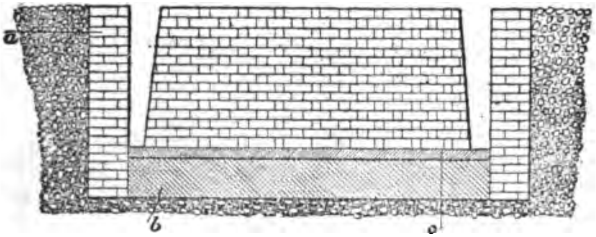
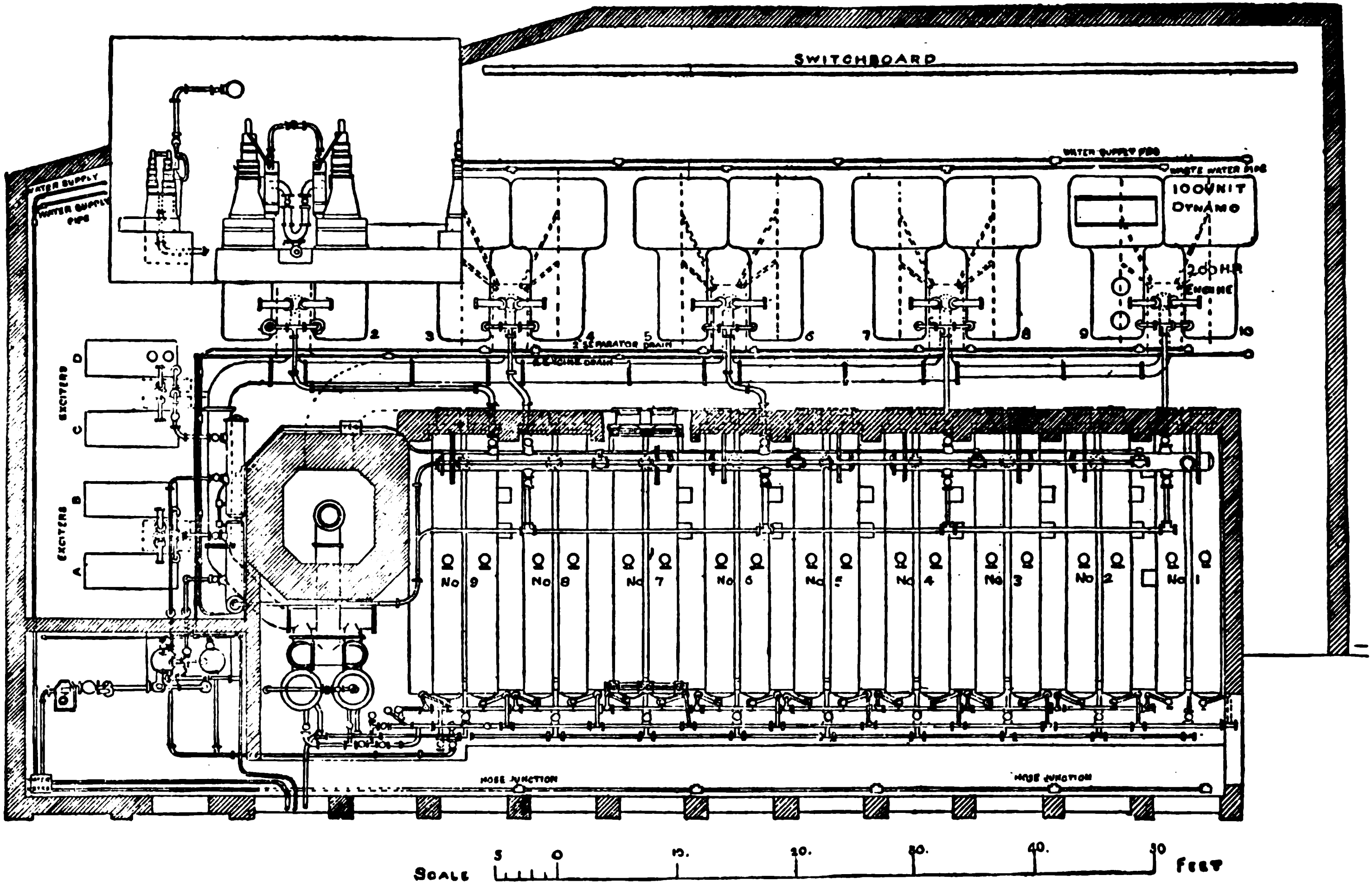


FIG. 82.—Manchester-square Station. Sectional view of the method of arranging the foundations so as to prevent vibration.
a, Retaining wall. *b*, Sub-base. *c*, Lead and felt.


SWITCHBOARD
WATER SUPPLY PIPE
WASTE WATER PIPE
100 UNIT DYNAMO
200 H.P. ENGINE
2
3
4
5
6
7
8
9
10
2 SEPARATOR DRAIN
2 ENGINE DRAIN
WATER SUPPLY
WATER SUPPLY PIPE
EXCITERS
D
C
EXCITERS
B
A
No 9
No 8
No 7
No 6
No 5
No 4
No 3
No 2
No 1
HOSE JUNCTION
HOSE JUNCTION
SCALE
5
0
10.
20.
30.
40.
50
FEET

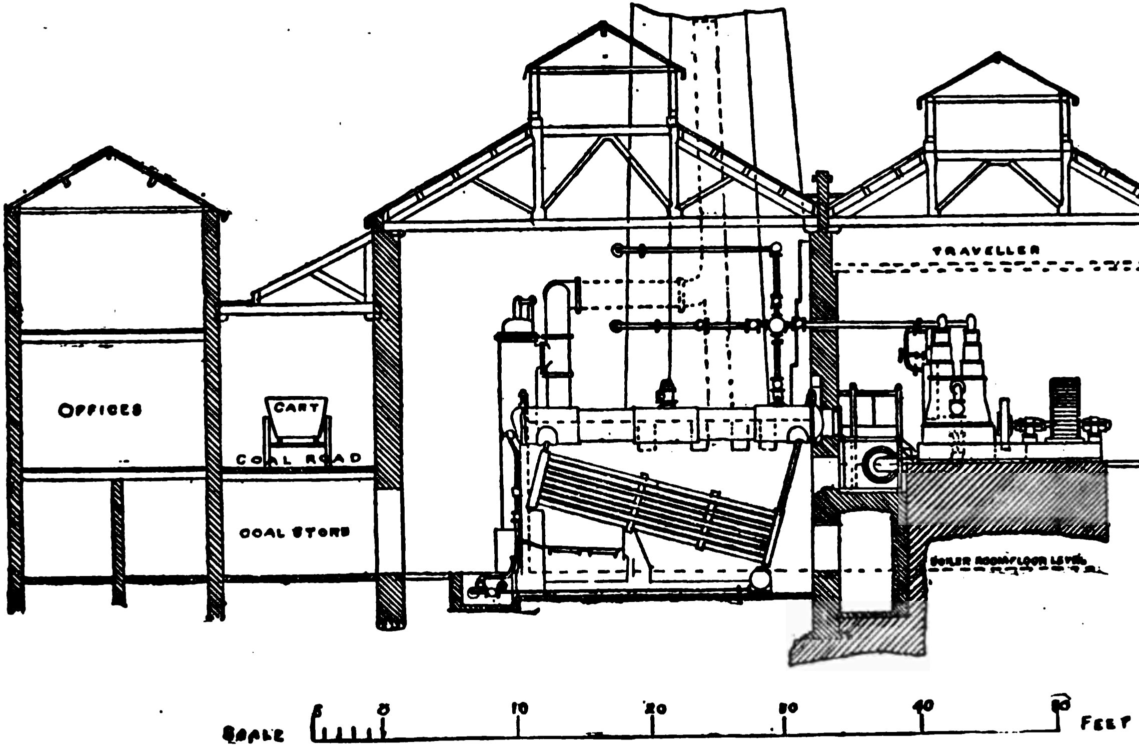


FIG. 84.—Manchester Square Station.—Section and Elevation.

is provided which will contain twelve hours' supply of water; but water can also be taken direct from the water mains. The coal store has a capacity for 300 tons of coal, and the coal waggons arriving from the street shoot the coal directly down into the bunkers, which are adjacent to the stoke holes. Hard by the boilers are the feed-water heaters and the pumps. Two Owen's pumps are provided, either one of which will pump all the water required for the boilers. The exhaust steam from the engines passes into an exhaust pipe, which is 15in. in diameter at one end and widens to 25in. in diameter at the other. The large end opens into the chimney shaft. In order to prevent the exhaust steam from mixing with the smoke, this exhaust steam pipe is continued right up the chimney, being supported centrally right throughout its length by rings built into the brickwork, which preserve it in position whilst permitting free expansion and contraction.

The shaft itself is 8ft. square inside at the bottom and 10ft. square inside at the top, and cased outside with white glazed bricks. The central exhaust steam-pipe is 26in. in diameter. The shaft is surmounted by a cast-iron chimney cap weighing 26 tons. This arrangement, which is due to Mr. Gordon, has the effect of abolishing the nuisance resulting from condensed steam and soot in the neighbourhood of the station. The exhaust steam not being contaminated with products of combustion dissolves quickly in the air. Adjoining the station is a house for the engineering staff, and when in full work the work will be arranged in three watches of eight hours each, and two watches on Sundays.

The whole of the station buildings are solidly built of brick, and lined with white glazed brick, like Sardinia-street.

We have next to notice the switch-board arrangements at Manchester-square. There are three switch-boards—one for the exciters, one for the dynamos, and one for the circuits. These boards are mounted on a partition which stands away from the wall of the dynamo room, and permits access to the connections behind the board. The working connections are mounted on enamelled slate bases, affixed to the wood frame of the switch-board. The dynamo switch-board is divided into ten panels corresponding to the ten dynamos. On each of these panels there is a main ammeter and ammeter short-circuiting plug, which ammeter reads the main primary current flowing out of each dynamo. There is also a Cardew voltmeter which reads the primary volts taken off one coil of the armature of each dynamo, and hence gives the total primary volts. Under each ammeter is a rheostat for introducing resistance into the field circuits of the dynamos, and thus regulating the electromotive force of each independently. At the bottom of each panel is a magnetic cut-out, the working arrangements of which are shown in Fig. 85. The primary current passes round the coils of the electro-magnets of this electro-magnetic cut-out. When the main current exceeds a certain safe value the attraction of an armature by this electro-magnet releases a double pole switch normally kept locked by a clutch, and the switch springs back and opens the circuit of the dynamos. The exciter board resembles a telephone switch-board. The object of the arrrangements is to group the exciters and dynamos. There are four exciters, one of which is sufficient for five dynamos. Hence at full load two exciters have to be operated. On the exciter board there are a series of vertical and horizontal bars which can be connected by plugs. The vertical bars are connected to the dynamo field circuits, and the horizontal bars to the exciter poles. By plugging together these strips any exciter can be put into the fields of any dynamo or dynamos as required, and the exciters can be arranged so as to work in parallel on one group of dynamos or separately on separate groups. There are the usual rheostats for introducing resistance into the fields of the exciters. The main circuit switch-board closely resembles that of Sardinia-street previously fully described. There are twenty-two circuits which proceed out from this board, and by means of plugs any dynamo can be put on to any circuit or group of circuits, and by means of a throw-over switch that circuit can be instantly changed on to a spare dynamo. There is one difference, however, in the circuit switch-boards at Sardinia-street and Manchester-square, in that the plugs in the circuit board in this last-mentioned station are made to screw into place for greater security instead of being simply plugged in as taper plugs. The twenty-two panels in this circuit board are all exactly similar. From this circuit board highly insulated cables pass out into a subway, where they are laid and fixed on wooden shelves. From this subway they pass into the iron

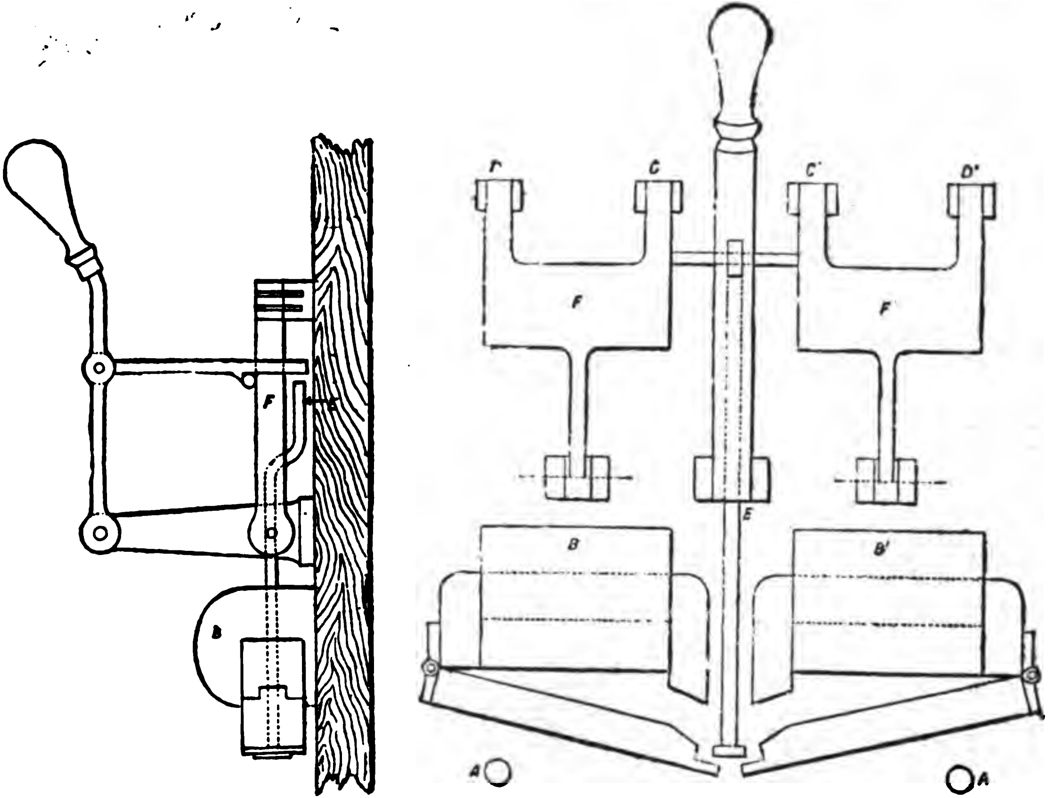


FIG. 85.—Magnetic Cut-Out at Manchester Square Station.

A, A, Dynamo Terminals. B, B¹, Magnetic Coils in Main Circuits. C, C¹, Contacts on Main Circuits. D, D¹, Contacts on Circuits of Dynamos. E, Releasing Rod raised by Magnets. F, F¹, Double Pole Switches, forced open by Springs when released.

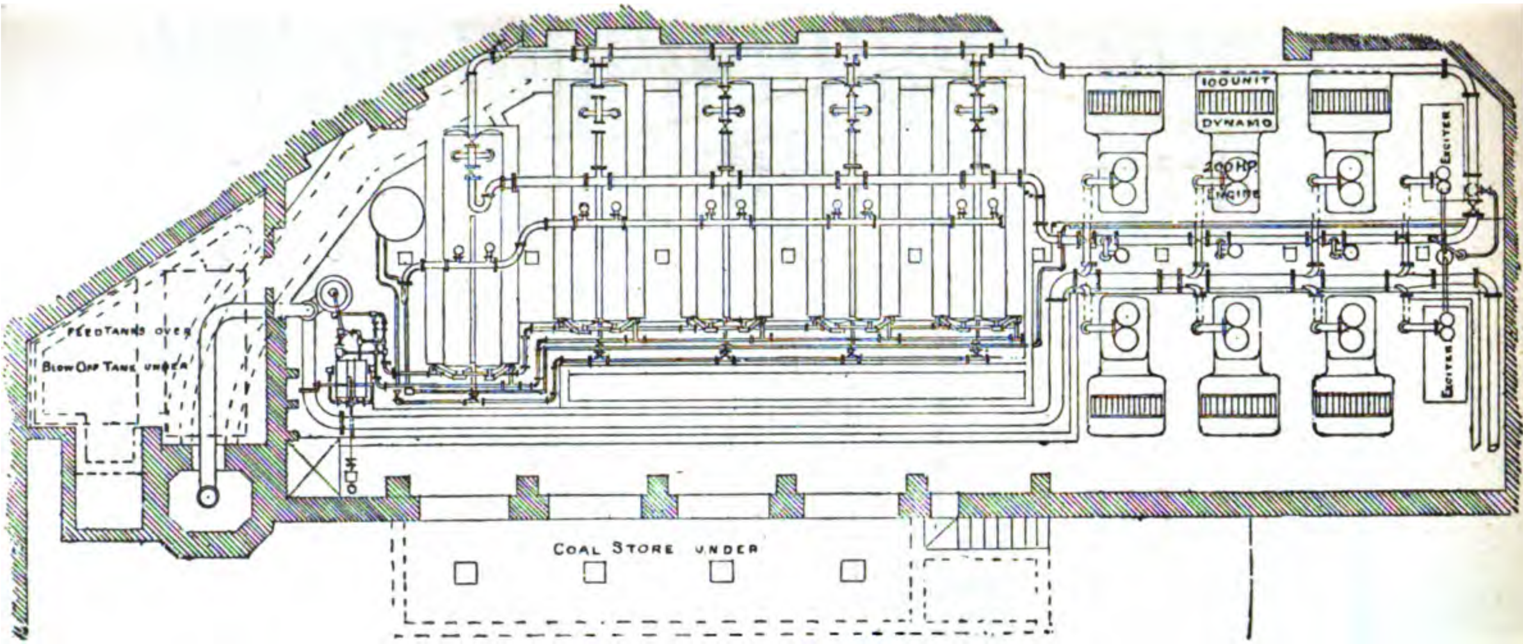


FIG. 86.—Rathbone Place Station.—Plan.

pipes laid in the streets, which have already been described in connection with the Sardinia-street station, otherwise the arrangement of mains is the same. The difficulties which have presented themselves at Manchester-square in dealing with the limited space at disposal have been overcome with great ingenuity, and it has required the exercise of much judgment to place 2,000 horse-power in a space so limited, having regard to the necessity for complete freedom from noise, vibration, and smoke.

RATHBONE-PLACE STATION.

This station (*see* Fig. 86) is, generally speaking, designed on the lines of Manchester-square. There are six Elwell-Parker 100-unit alternators, combined with Willans engines of the same size and make as those at Manchester-square. There are two combined Willans engines and Elwell-Parker dynamos as exciters, either one of which will do the whole work of the station. There are five Babcock boilers, each capable of evaporating 6,000lb. of water per hour, and the necessary pumps, heaters, &c. Rathbone-place was formerly a small private station which was taken over by the Metropolitan Electric Supply Company in 1888. The interesting point to notice about it is that whereas formerly the maximum possible output of the station was current for some 2,000 lights, by an economical utilisation of the space, and by the selection of the present plant, a possible maximum output of current for 15,000 8-candle-power lamps has been obtained. The station occupies the bottom floor of a factory, and great care has been exercised in the building construction, and by the introduction of a fire-proof roof, to render the station as free as possible from danger of interruption.

These stations of the Metropolitan Electric Supply Company are connected together by trunk mains, and in the summer, when the demand is small, it will be possible to shut down altogether one or more of these stations, and greatly to economise working expenses. At present the whole of these stations are working on the system of distributed transformers; when, however, a business has been built up, and the consumption in the areas of supply become sufficiently great, it is possible that a system of transformer sub-centres will be initiated, and be found to be advantageous.

§ 24. **The Thomson-Houston Transformer System.**—In the United States one of the most widely known of all the electric lighting companies is that of the Thomson-Houston Company, having its headquarters in Boston, United States. Commencing in 1880, and having in 1882 only a small factory at New Britain, Conn., this corporation has developed its electrical manufactures at a steadily increasing rate, and has at the present time an immense factory at Lynn, Mass., occupied in the production of electric lighting plant for arc and incandescent lamps, as well as for electric locomotion. In the United States over 50,000 arc lamps are operated by the well-known Thomson-Houston continuous current arc light dynamo, in some 600 or more stations. The ingenuity and remarkable inventive skill of Professor Elihu Thomson has been also brought to bear on the development of an alternating transformer system, with the result that nearly 100,000 incandescent lamps are in use (1890) in the United States in connection with a transformer system as devised by him. The alternating dynamo employed in the Thomson-Houston transformer system presents some interesting peculiarities.

Fig. 87 shows the general form of all the dynamos for generating alternating currents manufactured by the Thomson-Houston Electric Company. The field magnets are of cast iron, and are made in two parts, the lower one bearing the pedestals for the armature bearings. Each casting carries projecting inward from it one-half the total number of radial pole pieces. The number of polar projections varies from eight in some of the smaller sizes to twenty-two in the largest. The armature is a laminated iron cylinder, and has applied to its surface a set of flat coils which form one layer of double-insulated copper wire of square cross section. This armature winding consists of a number of flat oval coils, equal in number to the number of polar projections, wound in a lathe on special formers, and curved so as to fit the cylindrical surface of the iron core. There is a space of three-quarters of an inch or more in the centre of each coil which, in some machines, is filled with an insulating slip or core, and in others with a second separate coil used for exciting the field of the dynamo. The armature coils are securely bound to the armature core by German silver wire, and are covered with insulating strips of mica. These coils are either connected all in series and in series with the external circuit, as is shown in Fig. 88, in the case in smaller sizes of high potential machines, or they are wound, as shown in Fig. 89; *i.e.*, two groups in multiple, consisting of an equal number of coils in series. By this means a 1,300 light armature is wound with wire of the same size as a 650 lighter.

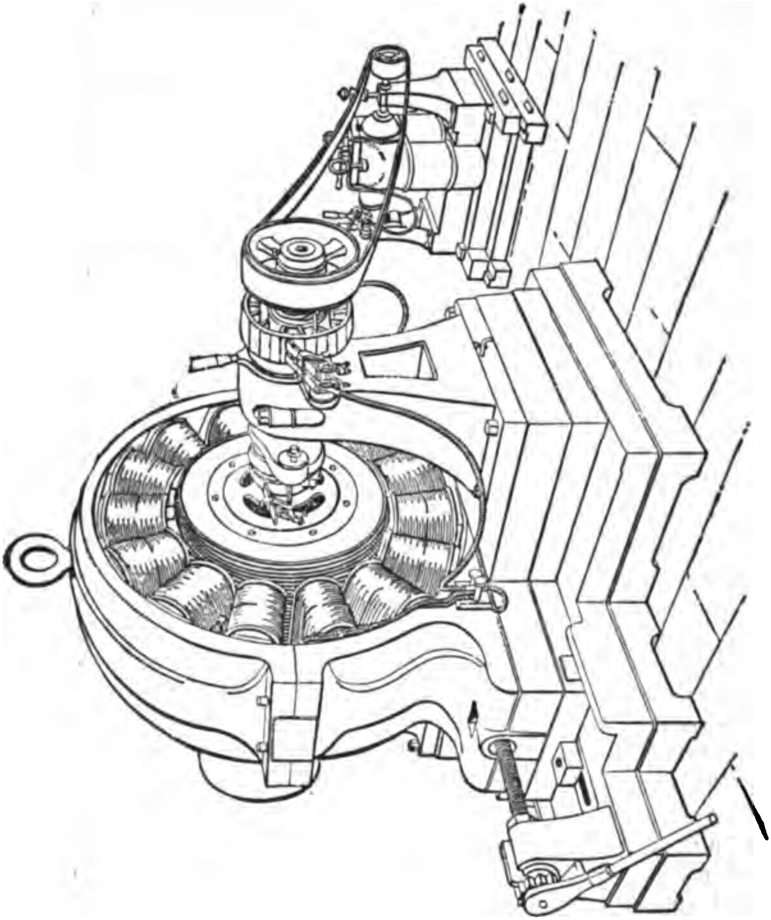


FIG. 87.—The Thomson-Houston Alternator.

The armature core, in these machines, is built up as usual of thin iron sheets perforated with apertures through the centre, so as to allow a circulation of air.

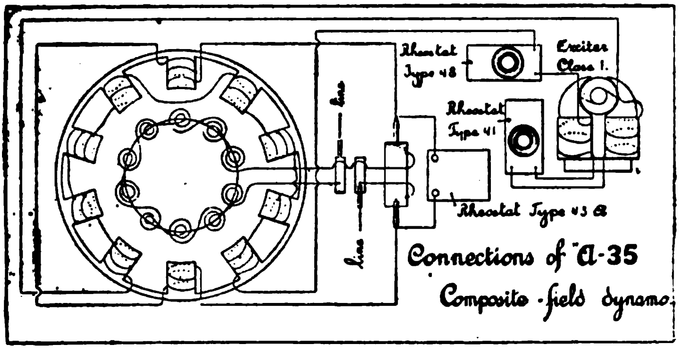


FIG. 88.—Connections in the Thomson-Houston Alternator.

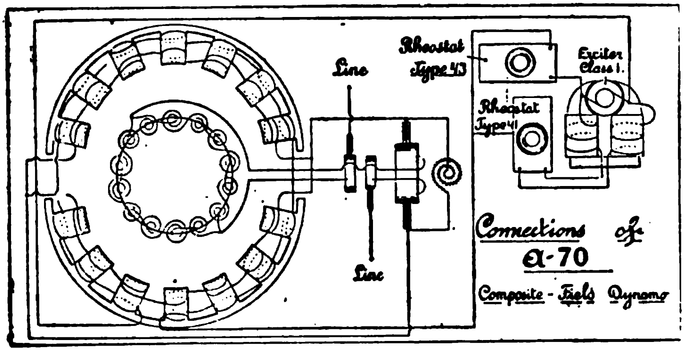


FIG. 89.—Connections in the Thomson-Houston Alternator.

These alternating current dynamos are made in three types, as follows:—

(i.) Self-excited.
(ii.) Separately-excited.
(iii.) Composite-wound.

(i.) *Self-excited Type.*—In this class of dynamo, which has been now more or less discarded in favour of the third mentioned, the field-exciting coils are coils wound about the armature in a manner like the ordinary Siemens' winding, and consist of but a very few turns of square copper wire. These coils are arranged as shown in Fig. 90, and they lie beneath the main armature coils and fill the spaces on the surface of the iron core between the wires of the flat or "pancake" coils as they are sometimes called. The upper sketch in Fig. 90 shows the manner in which these coils are wound over the ends of the core, the two opposite coils being either connected in series or in multiple arc, and their terminals brought out to a commutator on the shaft outside of the bearings at the collector end of the dynamo. This commutator has as many segments as there are poles on the dynamo, and the two terminals of the field exciting circuits on the armature are connected to alternate segments. The exciting current is controlled by a rheostat in its circuit mounted upon the switch-board, and in this circuit are included the coils on the field magnets. This design may, in fact, be described as an alternate-current armature winding on the top of a continuous current winding. This last supplies current for the field.

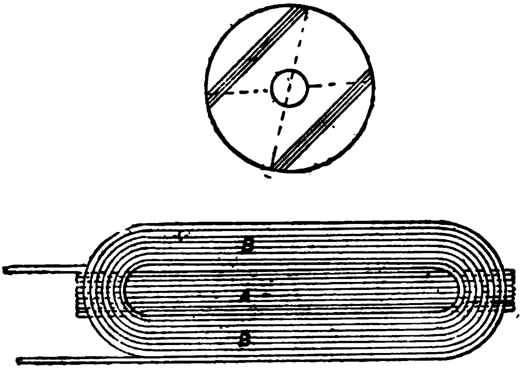


Fig. 90.

(ii.) *Separately-excited Type.*—The separately-excited dynamo is of the same form as the self-excited, the only difference being that in it the commutator and armature exciting coils are absent. It is used with an exciting dynamo, such as shown in Fig. 87.

(iii.) *Composite-wound Type.*—The term "composite" as applied to the third type of the alternating current dynamo of the Thomson-Houston Electric Company was adopted to distinguish this arrangement of field excitation from that employed in direct current machines, which consists in the combination, for producing the magnetic field, of the main armature current with a derived current shunted around the external circuit, or in compound winding. The arrangement of circuits which is used in the most improved type of Thomson-Houston alternator for maintaining a constant difference of potential at a defined point of distribution, regardless of load, is shown in Figs. 88 and 89.

A part of the magnetic field is maintained by means of current from a separate or exciting dynamo. If the load upon the outside circuit is increased it is necessary to increase the magnetism of the field, in order that the machine may in turn supply the increased demand in the circuit, and the lights remain steady.

This is accomplished in some other machines by varying the current of the field magnets by a rheostat or variable resistance operated by hand. In the Thomson-Houston dynamo, however, the same result is obtained entirely automatically by passing the greater portion of the main current through two or more of the field magnets, thus energising the machine in exact accordance with the demands made upon it. As an alternating current is not suitable for magnetising the fields it is necessary to change the character of the current produced in the armature to a direct current before passing it through the special winding on the field, and this is done by a commutator at the end of the shaft. By this arrangement the attention required at the dynamo is reduced to a minimum, while at the same time the regulation of the machine is perfected, and any number of lamps, from one to the full capacity, may be thrown on or off without in any way affecting the steadiness and brilliancy of those remaining.

To allow for a pre-determined percentage of loss in the wiring, it is necessary, as the load is increased, that there should be a definite amount of increase in potential, which is accomplished by placing around the field winding for the main current a resistance which shunts that portion of current not required for regulation.

This winding is precisely the same in principle as the compound winding in the case of a continuous current machine. In addition to the current derived from a small direct current separate exciter, a second current, which is a rectified portion of the main current, is used to energise the main fields. This current, being proportional to that in the external primary circuit, increases the field strength, and thus the potential, with increasing load.

It will be seen from the diagrams of the connections that the armature current is "rectified" for a part of its course by means of a commutator having as many segments as there are field poles on the machine—alternate segments being connected together, and one set connected to one armature terminal, and the other to the external circuit.

This rectified current is either used to excite two of the polar projections, as in Fig. 89, or to partially excite all of them, as in Fig. 88, the latter method being the most approved.

Before each machine is sent out from the factory, the strength of the compounding current is regulated by means of a German silver shunt fastened to the frame of the machine. By changing this shunt the machines may be made self-regulating for any required line resistance or drop, being over-compounded to whatever degree is needed. The winding may be described as that of a "compounded" alternator for giving constant potential at the ends of a line, or at the points of supply to the lamps.

The following table gives the sizes and capacities of the machines of this type thus far constructed, with the exciting and main current of each :—

Alternator.	Watts.	Lamp load in 16-c.p. lamps.	Exciting circuit.		Weight.	Speed.	Floor space (inches).	Output in amps.
			Volts.	Amp.				
A 35	35,000	650	100	5·8	3,570	1,500	66 × 45	35
A 70	70,000	1,300	100	11·2	8,270	1,070	84 × 56·5	70
A 140	140,000	2,600	...	...	...	680	80 × 105	140

Each machine yields current at 1,000 or 2,000 volts as required.

For the purpose of energising the field magnets the dynamos are furnished with small exciting dynamos of the direct-current type. It has been found desirable in some special cases to make the smaller sizes of alternating-current dynamos self-exciting, and to this end the armatures are wound with the extra or special coil before-mentioned for furnishing current to energise the fields. The exciter is usually placed, as shown in Fig. 87, behind the alternating dynamo, driven by a belt from a small pulley attached to the armature shaft. One exciter is usually employed with each alternating-current dynamo, but when several dynamos are operated in the same station it is often found more convenient to employ several exciters, any one of which is of sufficient capacity for all the machines. By this arrangement an accident to one exciter need not affect the general service.

Exciting dynamos are made in the following sizes :—

Class.	Volts.	Amperes.	Speed.	Weight.	Pulley Diam.	Pulley Face.	Floor Space.
0	100	12	2,300	307	4	2	24 × 13½
1	100	24	2,200	480	5	3	29¼ × 16⅛
2	100	40	1,800	696	6	4	31¼ × 18¾
3	100	60	1,600	1,080	8	5	37¼ × 21¾
4	100	80	1,600	1,364	8	6	40 × 23⅜

The current required for exciting the fields of the alternating-current dynamos is as follows :—

A-35 Composite Field, 5·8 amperes.
A-70 Composite Field, 11·2 amperes.

Systems of Distribution—Compensator System.—This system of distribution for incandescent lighting by alternating currents is the invention of Prof. Elihu Thomson, and was introduced before the transformer system had attained much commercial expansion. The principle of the system is shown in Fig. 91. An alternating-current generator usually wound for a potential of 330 volts delivers its current to the ordinary system of feeders and mains such as is employed in the direct two-wire system. At central points in the district to be lighted the compensators, or choking coils, are located—usually being placed upon poles at street intersections. A loss up to 10 per cent. of the dynamo potential, according to conditions, is allowed between the station and the lamps, and the pressure at the compensators is thus somewhat more than 300 volts.

The compensator consists of a laminated core of iron as in a transformer, wound with a continuous insulated conductor, the terminals of which are connected directly to the dynamo leads.

At three points in this coil, dividing the coils equally between its terminals, wires are attached leading to binding posts on the compensator frame. The terminals of the coil are attached to similar binding posts, and from these five points are run lamp circuits, which may be two three-wire systems. The fall of potential through the compensator from one lead to the other will thus be divided into four equal parts, and the voltage in each lamp circuit will be, therefore, about 75 volts. It is evident that many variations may be made in this arrangement; the coil may be divided into any number of equal portions, and from them the circuits may be run on the 3, 4, 5, &c., wire-systems, or the various circuits may be on the simple two-wire system. We take, for explanation, however, this 330 volt two 3-wire system, as it was the one most used, and serves

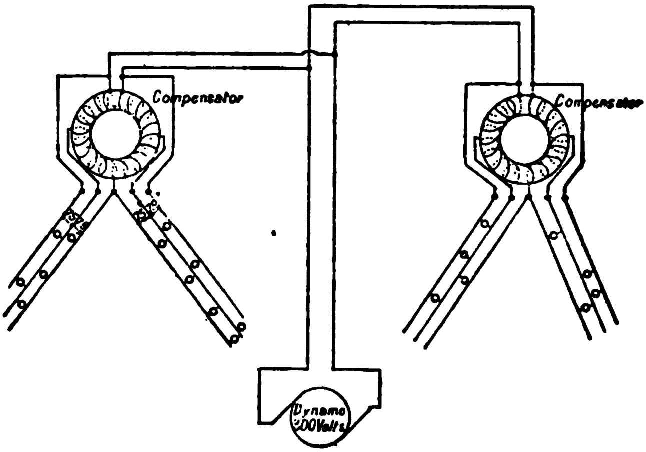


FIG. 91.—Prof. Elihu Thomson's "Compensator" System of Incandescent Lighting.

as well as any other to illustrate the principle of the arrangement.

Considering Fig. 92:—There are, at maximum load, say 8 lamps on the compensator; when they are all turned on, a very slight current traverses the coils of the compensators, the self-induction of its coils of wire wound about soft iron being so high as to practically prevent any current flow. Consider now that all the lamps on one of the three-wire circuits be turned off, the conditions are as in sketch 2, Fig. 92.

The current traversing the part of the coil "A" acts as the primary of a transformer, the secondary being the part "B"; transformation from 150 volts in the primary to 150 volts in the secondary thus takes place, and one-half the current in the lamp circuits is due to the dynamo current, and one-half to that part of the compensator marked "B." The part "A" thus needs to carry only sufficient current for one lamp, and the regulating capacity of the compensator is seen to be four times the carrying capacity of its wire. If the lamps be arranged as in sketch No. 3, the first part of the compensator marked "A" will carry $\frac{6}{4} = 1\frac{1}{2}$ times the current required for one lamp. The ratio of conversion in this case being 1 : 3, the part of the compensator marked "B" will supply $\frac{1\cdot5}{3} = \cdot5$ times the current for one lamp.

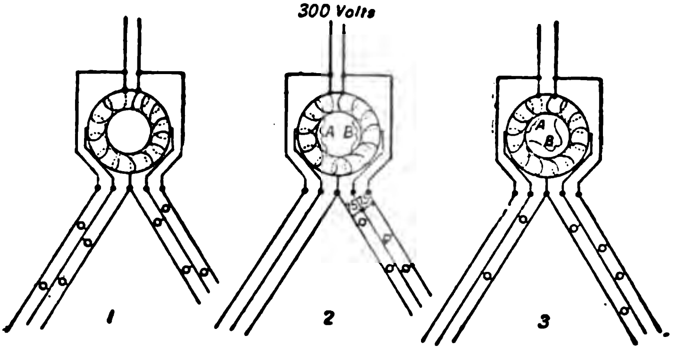


FIG. 92.—Three-wire Compensator System.

In this way the action of the compensator for any arrangement of load may be readily deduced. In few words, it may

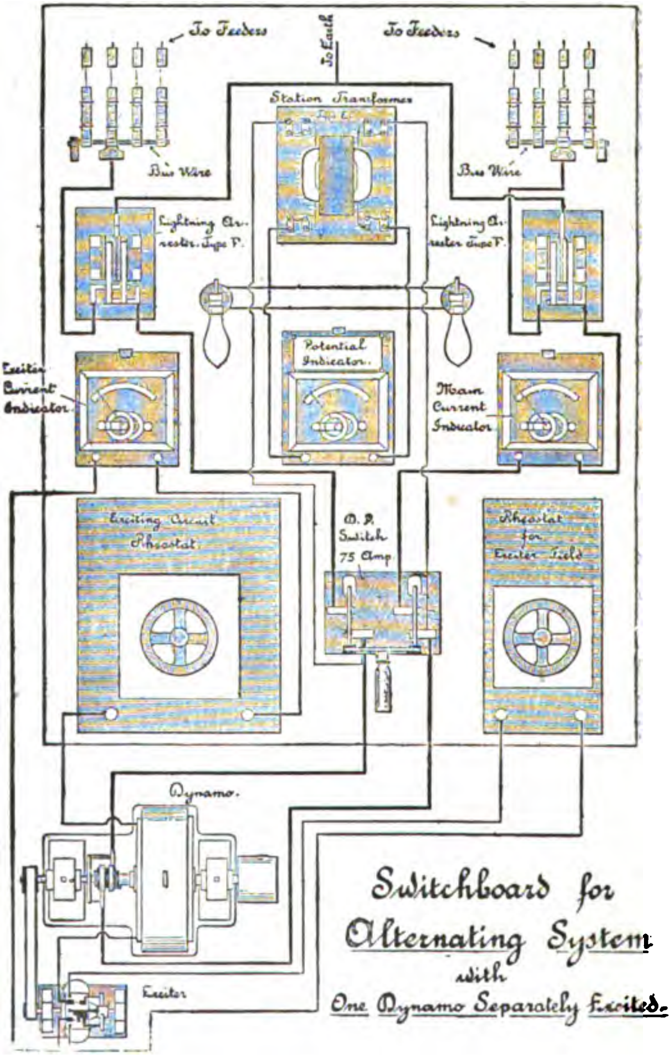

To Feeders
To Earth
To Feeders
Station Transformer
Bus Wire
Bus Wire
Lightning Arrester. Type F.
Lightning Arrester Type F.
Exciter Current Indicator.
Potential Indicator.
Main Current Indicator
Exciting Circuit Rheostat
D. P. Switch 75 Amp.
Rheostat for Exciter Field
Dynamo.
Exciter
Switchboard for Alternating System with One Dynamo Separately Excited.

Fig. 93.—Switchboard for Thomson-Houston Transformer System.

be described as a combination of a transformer with a system of direct distribution.

The chief objection to this system is, of course, that it brings the high potential of the dynamo to the house wires.

The compensators have been manufactured in two sizes, one for 75 and the other for 150 lights. These figures, however, do not denote the maximum number of lamps which may be operated from a transformer, but merely the amount for which the compensator will regulate, *i.e.*, the maximum allowable difference in the number of lamps connected to its circuits.

Transformer System.—The transformer system of the Thomson-Houston Electric Company is, like all other such successful systems, a constant potential one; the pressure employed being usually 1,000 volts. The dynamos are constructed to give 1,100, so that 10 per cent. may be allowed for loss in the primary and secondary circuits. As before stated, the dynamo is usually of the compound or "composite" type, the fields being excited by the rectified current from the alternator as well as by that from a small direct current dynamo.

In other respects this system is similar to other transformer systems, and its principle needs no special explanation. Fig. 93 shows the form of switch-board employed. The various instruments which comprise it will be presently described. The dynamo has already been described. The standard type of alternator is the separately-excited drum armature alternator, compounded to give constant pressure for a drop of a definite number of volts in the primary line between no load and full load. This alternator is excellently designed in all its parts, and between full and no load can maintain constant potential at the end of its primary line.

Transformers.—The latest form of transformer manufactured by the Thomson-Houston Electric Company is shown in its box in perspective in Fig. 94. The coils are enclosed in a cast-iron box, waterproof, and stout enough to withstand ordinarily rough usage. The primary wires are seen coming out of the transformer at the top, and the secondary at the bottom, each passing through waterproof insulating bushings.

The coils are in some cases wound directly upon the cores, in others they are wound on wooden formers, which are removed when the coils are completed. In some forms the secondary winding is laid on first and the primary over it; in other forms the two are wound side by side. In either case the insulation between the two coils is very carefully made, consisting of mica, paper, and shellac. The secondary coil is wound with two equal circuits, which may be either connected in series to give 104 volts or connected in multiple arc to give 52. Fig. 95 shows the switch device by which these connections are made and the fuse wire terminals for holding the safety cut-out for the secondary circuit.

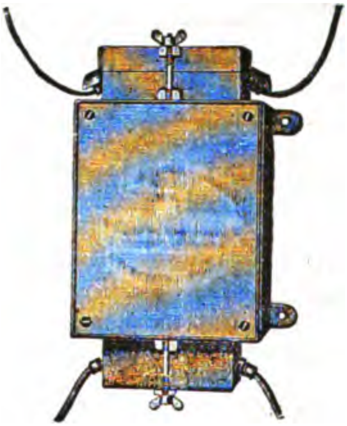


FIG. 94.—Thomson-Houston Transformer.

Various devices have been invented by Prof. Elihu Thomson for preventing, by any possible chance, the connection of the primary high potential circuit with the secondary. In 1885 he took out a patent for a "Sheath" protective device, in which a copper strip or divided plate connected to the earth is interposed between primary and secondary windings. Another device is to ground one end of the secondary circuit, as described in Prof. Thomson's United States Patent Specification, No. 322,138, of 1885;* the latest arrangement, however, is the application of the film cut-out (described further on in connection with the series socket) to automatically ground the secondary circuit in case the high potential reaches it.

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* *See* letter in *Electrical Review*, Sept. 26, 1885, by J. A. Fleming, and subsequent correspondence.

The objection to the film device is that it is apt to be broken down in case of a lightning discharge reaching the line before the lightning arresters have a chance to operate. On underground circuits the film device can be used without any such risk.[*]

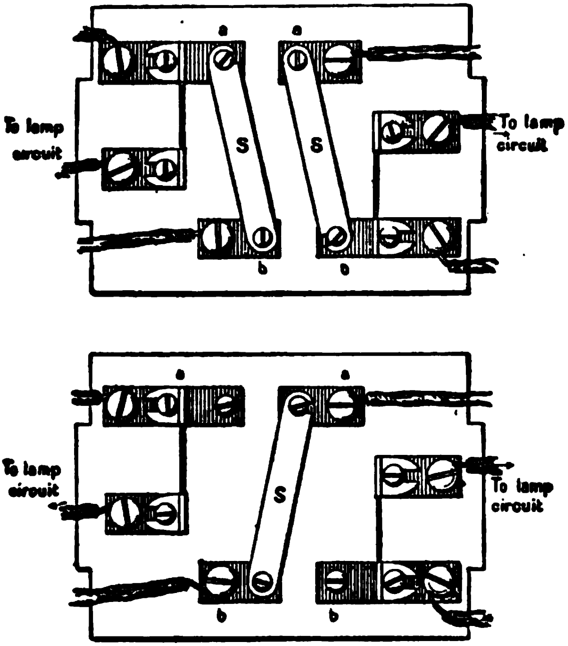

FIG. 95.—Connections on Thomson-Houston Transformer.

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[*] A recent practice of the Thomson-Houston Company in the installation of transformers is to enclose them in a box filled with a highly insulating oil, which permeates the insulation of the coils, keeps out moisture from the same, and renders it necessary that a very considerable difference of potential should exist between the primary and secondary coils in order that a discharge from one to the other may take place. Such coils are very much more secure from breakdowns due to lightning than coils mounted in the ordinary manner. At the same time, the insulating materials used to insulate the coils from each other and from the iron core may be of very much less expensive character and require less labour to put it on. The United States patent for this method of mounting the transformers in oil was filed May 27th, 1887, and issued May 27th, 1890, as Patent 428,648. It is interesting to note that the more recent proposals of using high potential transformers for power transmission in Europe involve this feature of oil insulation.

Figs. 96, 97, 98, 99, 100 show the various forms of cores which have been used in these transformers. Figs. 96 and 97 show a type in which the coils are wound about two cores of

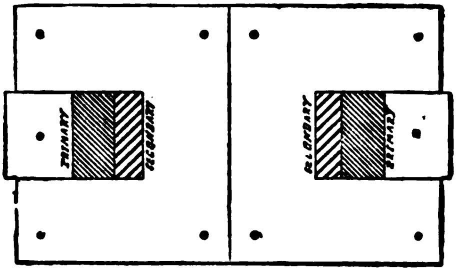

FIG. 96

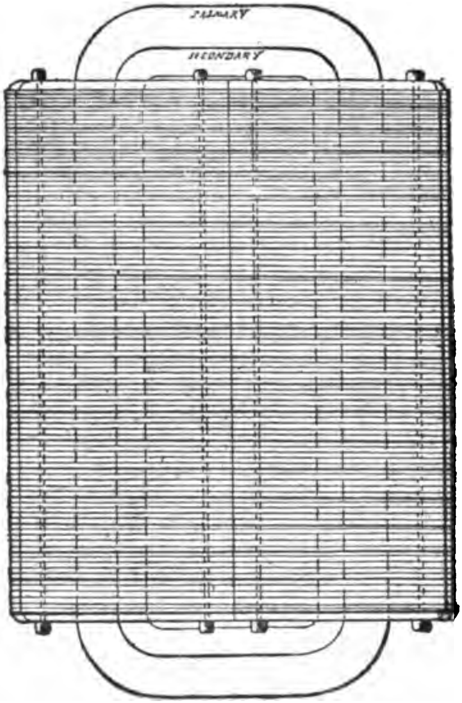

FIG. 97.

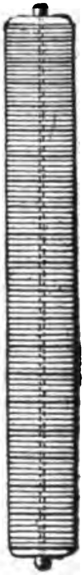

FIG. 98.

similar shape, placed back to back, and each built up of C-shaped laminæ. Laminated plugs are driven into the openings over the coils, and the whole securely fastened together with bolts.

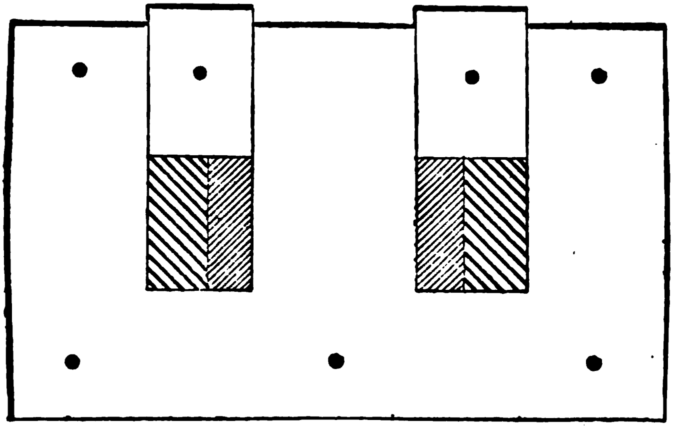

Fig. 99.

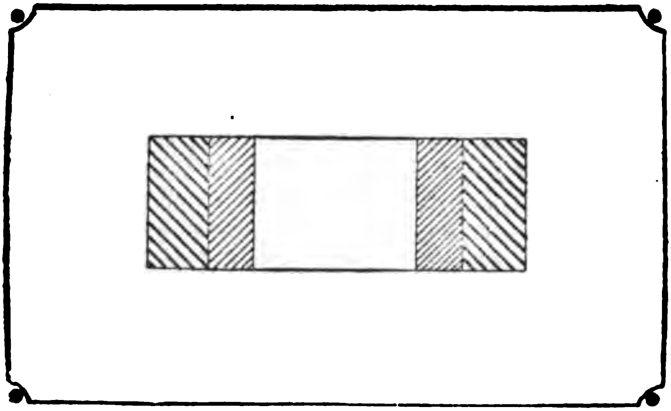

Fig 100.

Fig. 99 shows another form of core in which the coils are wound on formers and then driven over a tongue projecting from a core built of "E"-shaped laminæ. Laminated plugs are driven into the openings over the coils. This is the type of core employed in the type "E" transformer shown in its box in Fig. 100.

Fig. 100 shows the latest form of core. A plug of laminated iron is placed in the centre of a transformer coil, and sheets of iron cut in the form of a hollow rectangle are placed about the coil. These squares fit the plug very closely, and render the magnetic contact very perfect. No insulating sheets are used between the laminæ of the transformer cores, the oxide of iron formed on the sheets during the annealing process being considered to be sufficient insulation for eddy currents.*

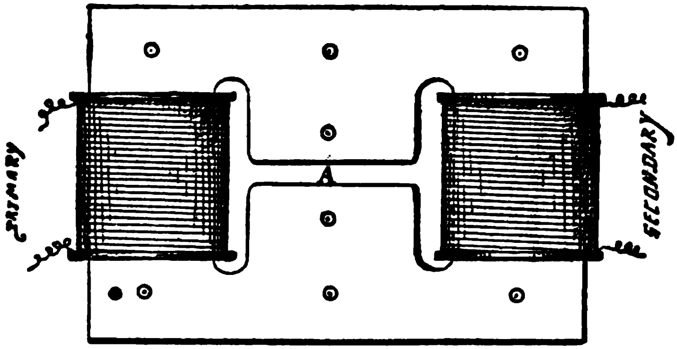

FIG. 101.—Constant-Current Thomson-Houston Transformer.

A novel device due to Prof. Thomson is employed in the transformers for maintaining the induction of the cores in the plane of the laminæ; zinc sheets, equal in thickness to two or three laminæ are introduced in the core at intervals of five sheets of iron. The magnetic resistance of these sheets prevents any distortion of the lines of induction, and serves materially to increase the efficiency of the apparatus. These sheets are shown by the heavy lines in Fig. 97 of the transformer. The primary and secondary fuses are contained in the ends of the iron cases, access being obtained by lids which can be screwed down. The primary fuses are mounted on porcelain, and the secondary also on porcelain bases. It is remarkable to note how short these primary fuses are. The possibility of using such short fuse wires is dependent on the use of a dynamo of considerable self-induction.*

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* In more recent practice very little scale is allowed to exist on the iron, as its presence in any amount gives rise to increased hysteresis.

Constant-Current Transformer.—Figs. 101 and 102 show two forms of transformer adapted for transforming from a constant potential primary current to a secondary current of constant strength, the potential of the secondary varying with the number of lamps in circuit.

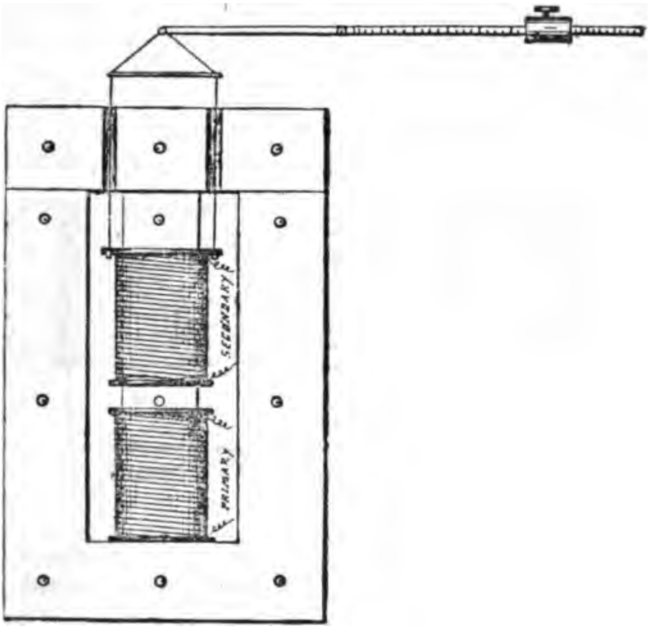

FIG. 102.—Constant-Current Thomson-Houston Transformer.

Fig. 101 shows a type in which the coils are wound about opposite ends of a peculiarly-shaped soft iron laminated core. This core is designed so that the magnetism induced by the primary is partially carried through that part of the core enclosed by the secondary circuit, and partly through the air-space "A." The transformer core is properly formed and proportioned, so that any decrease in the number of lamps on the secondary circuit by decreasing the secondary circuit resistance increases the reaction of the same on the primary, and causes a greater leakage of magnetism across the air space "A." This cuts down the induction in the secondary and increases the self-induction of the primary, thus proportionally decreasing its current.

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* In more recent practice a special arrangement of fuse is employed, which prevents arcing.

Fig. 102 shows an ingenious device invented by Prof. Thomson, for maintaining a constant secondary current. It is upon the same principle as the arrangement often used in laboratory experiments, consisting of a secondary coil balanced on a scale arm over a primary coil, the secondary being connected in series with an incandescent lamp. When an alternating current is sent through the induction coil the lamp coil is repelled, and adjusts its own height above the primary induction coil, in accordance with the induction in itself, and maintains the current in itself constant even for varying primary current by its changing distance.

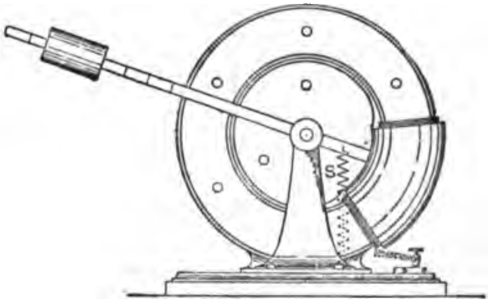

FIG. 103.—Balanced Reactive Coil.

The secondary coil of the transformer in question is movable on the core, and is supported by a rod from a lever bearing an adjustable counter-balance. At full load the counter-balance is so placed as to allow the secondary to lie close to the primary. If the secondary resistance be decreased its current increases momentarily enough to cause the secondary coil to be repelled from the primary and to assume some position above the latter at which point its reaction is the same as before, and its current again becomes normal.

A third device used for the same purpose as the above, but of a different nature, is shown in Fig. 103. A reactive coil, as is shown in Fig. 104, and explained under the head of regulating devices, is connected in the circuit of lamps in series on a constant potential system. Its sheath is counter-balanced by the weight P, and the weak spring S holds the sheath over the coil under normal load. On the extinction of a lamp in the circuit the reaction of the sheath on the coil increases and the sheath is repelled, thus increasing the self-induction of the coil and reducing the lamp current to its proper amount.

Regulating Devices.—Reactive Coil or Dimmer.—This is a device used in alternating current work to serve the same ends as rheostats in direct current plants. They are used in central stations for adjusting the potential of the feeders, and in theatres for controlling the candle power of the lamps.

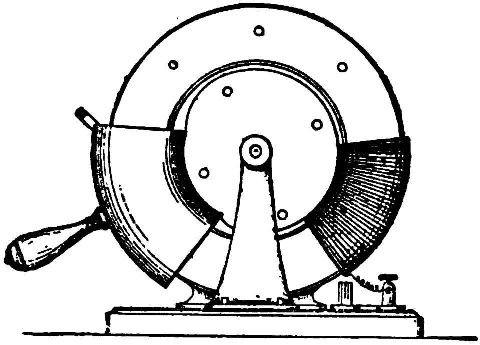

FIG. 104.—Reactive Coil or Dimmer.

They are, in principle, choking coils in which the winding is wound about a laminated soft iron ring, and in which a heavy envelope of copper adjusts, by its position as regards the coil, the self-induction exerted by it.

Fig. 104 shows the general form of the reactive coil. A winding of well-insulated copper wire of comparatively few turns surround one part (about one-eighth of the circumference) of a laminated iron ring. Inside the ring is a laminated iron drum, supported in bearings and fitting the inside of the ring not very closely. A copper sheath is fastened to this drum, and is rotated about with it. When the sheath is over the coil, its width is just sufficient to completely cover the coil.

This sheath, mounted upon the drum, forms a closed coil of very large section, around the ring, and fits closely, leaving but a small clearance space.

The action of the dimmer will be evident from what has been said of its construction. When the sheath is over the coil, the latter is in the same condition as the primary of a short-circuited transformer, and offers but slight impedance to the flow of current. In some dimmers the coil is short-circuited when the sheath is in this position. When the sheath is rotated away from the coil its reactive effect is diminished, and the impedance of the coil is increased; when it is in its furthest position from the coil the magnetic field of the latter is closed through the drum-shaped core and its impedance is very great.

This same device, of a movable secondary of one turn of heavy metal, has been used as a transformer for electric welding work. In this case the sheath is not itself a closed circuit, the terminals being connected to the pieces to be welded.

The principle which underlies this regulating apparatus is simply that the presence of a closed secondary circuit over the primary coil greatly reduces the impedance of the primary circuit in question. When the sheath is directly over the primary it is traversed by very heavy induced currents, and hence there is a certain waste of energy in employing such an apparatus; but it has great advantages over a simple graded choking coil, in that the impedance can be varied continuously and without breaking circuit.

§ 25. **Station Appliances in the Thomson-Houston System.**—*Earth Detector.*—Every switch-board is provided with an earth-detector, by means of which an "earth" or "ground" may be detected if existing on the primary mains. This apparatus is shown in Fig. 105. It consists of a small transformer, mounted on a board with a lamp on its secondary circuit and with a two-way switch. One end of the primary wire of this small transformer is permanently connected "to earth," and the other primary terminal can be connected by the switch to one or other of the two primary mains at pleasure. If an earth exists on one side of the main primary circuit, then when the testing transformer has its ungrounded pole put to the other main, the lamp in its secondary circuit will light up, because current finds its way through to earth in flowing through the primary coil of the testing transformer. The lighting of the lamp when the switch has one position or the other not only indicates a "ground," but shows which primary main it is on, provided that the fault is of sufficient magnitude to let out primary current enough to operate the lamp on the secondary of the testing transformer.

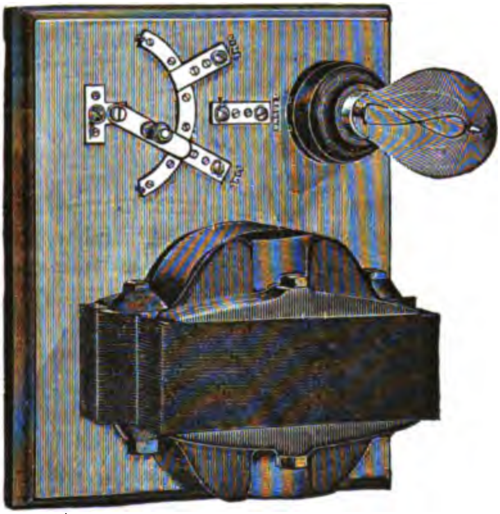

FIG. 105.—Ground Detector.

Station Transformers.—On the switchboard is also mounted a transformer, which provides current for lamps to light the switchboard, and also, by connection with a voltmeter, enables the primary pressure in the station to be measured.

Lightning Arresters.—All overhead primary circuits are provided with lightning arresters, both at the station end of the line and at the transformers. The principle of these instruments, of which the station lightning arrester is shown in perspective in Fig. 106, is the same as that of the well-known Thomson-Houston lightning arrester which has been so long and successfully used in connection with the arc-light system of the Thomson-Houston Company. This arc-circuit lightning arrester is shown in Fig. 107, and consists of an electro-magnet, the coils of which are in series with the arc-light circuit. In between the poles of this magnet, but well insulated from them, are a pair of curved metallic horns.* One of these horns is in connection with the line and the other in connection with the earth. If a lightning discharge strikes or, as is more often the case, inductively acts on the line, the inductance of the electromagnet blocks the path of the discharge, and it leaps across the air-space between the horns and goes to earth. In doing this, an arc would start between the horns, were it not for the fact that a strong magnetic field is produced by the electromagnet in this air-space, the lines of force of which

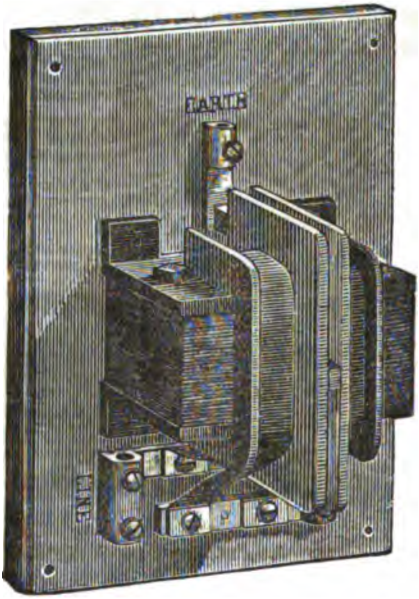

FIG. 106.—Station Lightning Arrester.

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* For the use of this block (Fig. 107) the writer is indebted to Messrs. Laing, Wharton, and Down, and he takes the opportunity at the same time of acknowledging the kindness of Mr. J. W. Kirkland, of the Thomson Houston Electric Light Company, in the United States, in furnishing, by permission of Prof. Elihu Thomson, sketches and detailed information on the Thomson-Houston system, which has rendered it possible to make the above descriptions much more complete than they would otherwise have been.

are perpendicular to the path of the discharge. The arc is, therefore, pushed forward along the curved horns, and finally blown out or extinguished. This highly ingenious apparatus stands guard over the arc-light dynamo; and, by placing one on each end of the arc line, the dynamo and switchboard is effectually protected from discharge due to lightning. Quite the same principle is applied in the station and transformer lightning guards shown in Figs. 106 and 108. The connections of the transformer guard are shown in Fig. 108. The two primary wires proceeding to a transformer enter the lightning protector

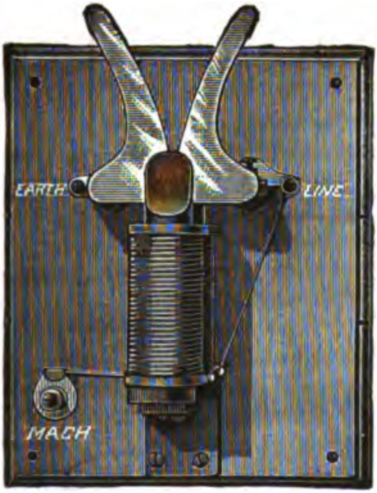


FIG. 107.—Thomson-Houston Arc-Line Lightning Protector.

at the terminals *a b*, and are connected with the transformer through the pipe *c*. To each of the terminals *a* and *b* is connected one end of the coil of an electro-magnet *d*, the other end of which is attached to a terminal placed near to a metal plate connected to earth. If a lightning discharge affects the line it could cause an arc to start between the earth plate and each of the terminals of the electro-magnet coils near it. These magnets are, however, so arranged that the magnetic field created by the current then started through them will blow out the arc and stop the discharge. All transformers which are fed from overhead primary lines are protected in this manner.

Distribution System.—A very large portion of the transformer lighting of the Thomson-Houston Company in the United States is carried on by means of overhead or aërial primary lines. The usual working pressure on the primary circuits is 1,000 volts. In setting out these lines several main primary lines are run to iron feeder boxes (*see* Fig. 109), and from these boxes distribution primary lines are run to groups of transformers. Fuse wires or cut-outs are inserted in

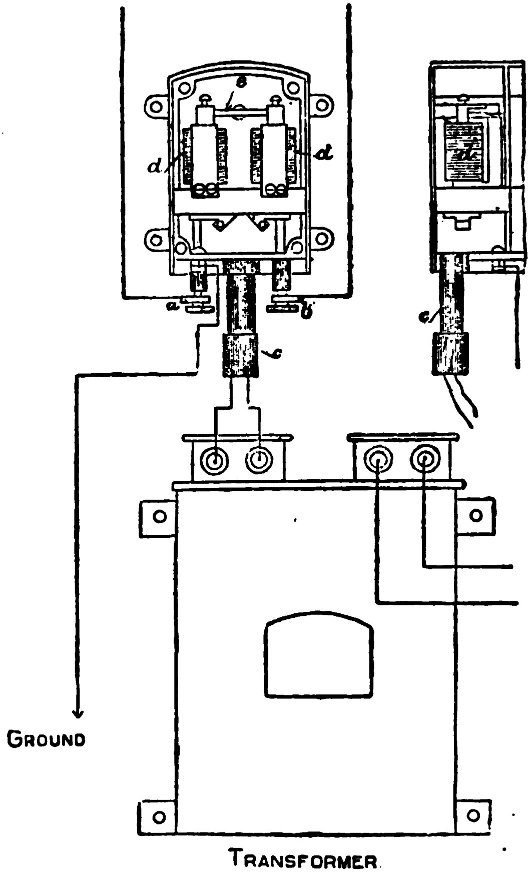


FIG. 108.—Connections of Transformer Lightning Arrester.

the feeder boxes. The transformers are placed in the buildings or are attached to the external walls of buildings, and these transformers are enclosed in cast-iron boxes which have weather-tight lids at both ends covering receptacles in which are placed the primary and secondary fuse wires of the transformers. The secondary fuse wires are generally mounted on a porcelain base and the primary ones also. A special switch permits the transformer to be cut out of circuit whilst changing the fuses.

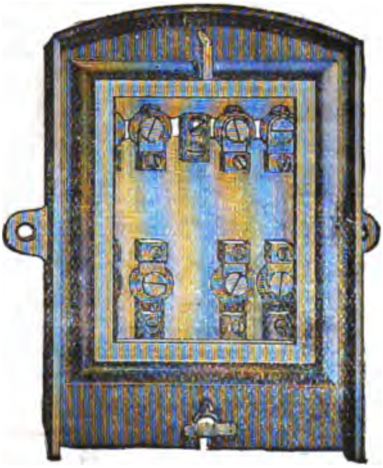
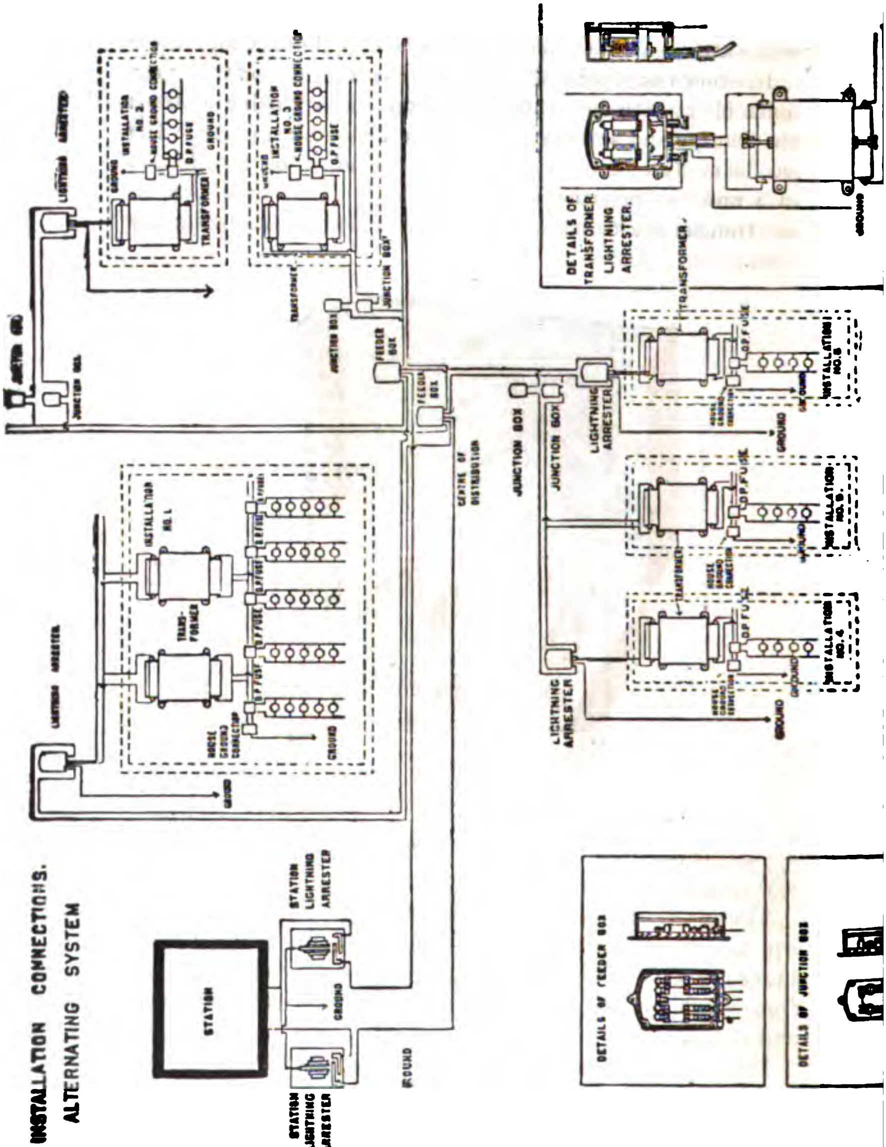


FIG. 109.—Feeder Box.

A general plan of an installation of alternating current apparatus is shown in Fig. 110. Starting from the station the wiring is as follows:—

The primary lines, protected by station lightning arresters, are run from the dynamo to the centres of distribution where feeder boxes containing the necessary safety fuses are interposed, and from which run the mains for the supply of the transformers and lamps.

Before the current for any group of lamps is taken to the transformer, it passes through a junction box, from which the lines lead directly to the primary connections of the transformer. To the secondaries of the transformers, the wires for the direct supply of the lamps are attached. Before the current



INSTALLATION CONNECTIONS. ALTERNATING SYSTEM reaches the lamps it passes a double pole cut-out box provided with safety fuses and the automatic protective device.

In every installation of alternating current apparatus, use is made of transformer lightning arresters, connected as shown in the diagram. Each feeder box has a sliding glass cover, which can be easily removed to replace or change fuses, and permits of a ready examination of the interior. The connections are so arranged that the box may be cut completely out of circuit during such changes.

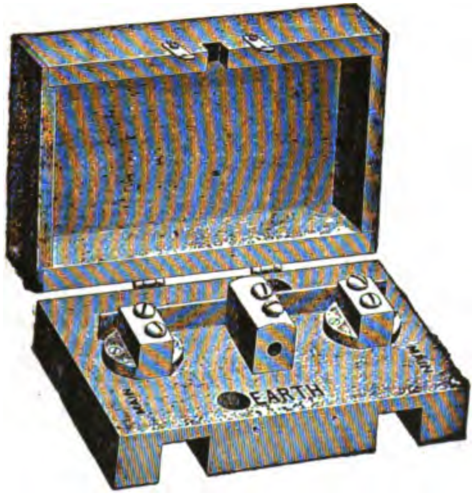


Fig. 111.—Thomson Protective Device.

The Thomson-Houston Electric Company, in all installations of alternating current apparatus for incandescent lighting, employs the Thomson Protective Device (shown in Fig. 111). It is a simple but effective appliance for removing the possibility of accident which might arise from contact of persons with the secondary circuit. It is also a preventive of fires by leaky secondaries.

There are three conditions which must be simultaneously satisfied before this possibility can be said to exist.

1. There must be a ground on the primary wires.

2. There must be a contact between the primary and secondary coil in the transformer.

3. The person must be in contact with the secondary and with the earth at the same time.

The fulfilment of the first of the above conditions is of not uncommon occurrence, and the presence of a ground can be easily detected, and means can be at once taken to remedy the trouble.

The second condition is met with seldom, but is only liable to occur when transformers are injured or subjected to rough usage in shipment, or by the effects of lightning.

The remoteness of liability to accident is quite apparent when it is remembered that these conditions must be simultaneously satisfied, and even then the extent of the injury depends upon the relative position of the contacts with reference to the two primaries.

As the fulfilment of the above conditions is, of course, not beyond the range of possibility, the device herewith described has been designed to prevent any injury resulting from a contact with the secondary wires when these requirements are fulfilled. It consists of three base terminals, to the central one of which is rigidly attached a flat brass spring pressing against the two outside terminals, but normally held out of contact with them by slips of Thomson paper film. This paper film is very carefully prepared so that it readily withstands the pressure of the spring, but is instantly ruptured when the first and second conditions, mentioned above, are satisfied. To the central terminal is attached, by means of a binding screw, a wire connected with the earth. To the outside terminals the secondaries are led directly from the transformer. The paper film is perfectly insulating for the pressure of the secondary current, but if the difference of potential between the earth, with which the brass spring is in contact, and either one of the terminals, to which the secondaries are attached, should rise beyond the normal pressure, the paper film is at once punctured. This results in short-circuiting the secondary, which causes the primary fuse to blow, thereby cutting out the entire circuit.

§ 26. Station Measuring Instruments.—In connection with the Thomson-Houston transformer system there are some very ingenious measuring instruments specially devised for alternating currents. There is, for example, an amperemeter and voltmeter (*see* Figs. 112 and 113) which act on the same principle. A light brass arm, swinging on almost frictionless bearings, moves in a vertical plane, and carries at its extremity a small horse-shoe, or U-shaped piece, of soft iron. A flat circular bobbin of wire, wound on a split brass spool, is fixed with its plane vertical, but centred eccentrically situated with respect to the pivot of the needle. The U-shaped piece of soft iron embraces the coil, and its motion round the pivot is constrained to be simply a movement nearer to or further from the inside surface of this circular coil. When a current passes through the coil of wire it creates a non-uniform magnetic field in the interior of the coil which is stronger near the inside surface of the coil than it is at points nearer the centre of the coil. The soft iron tends to move from places of weaker to places of stronger field, and in so doing moves the arm to which it is attached round its pivot, and displaces the index arm. This arm carries a counter balance so fixed that the magnetic force on the iron is opposed by a force due to gravity, and the position which the needle takes up under the influence of these opposing forces is one

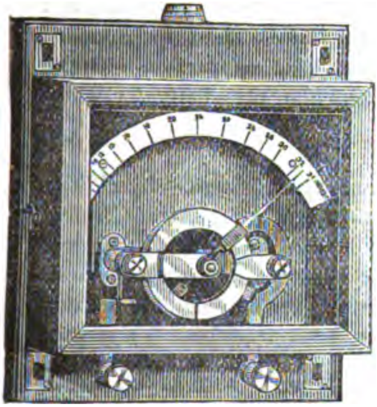


FIG. 112.—Alternating-Current Ammeter.

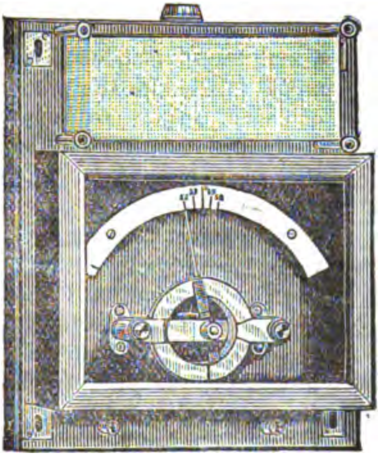


FIG. 113.—Alternating-Current Voltmeter.

which is dependent on the strength of the field in the interior of the coil, and therefore of the strength of the current in the coils. The force on the iron due to the current in the coils is one which depends partly on the strength of the field at the spot where the iron is and partly on the rate of variation of this field from point to point in the circular space. If the spool is wound with coarse wire the instrument may be graduated arbitrarily, and by comparison with a standard as an amperemeter. If the coil is wound with fine wire, and has a German-silver resistance coil in series with it, then the instrument may be graduated as a voltmeter. In the station such a voltmeter is worked off the secondary of a small reducing transformer, which takes current from the mains, and serves to measure the primary pressure. These instruments, of course, require to be graduated by comparison with an electro-dynamometer for the particular periodicity for which they are to be used.

§ 27. **Street Lighting by Incandescent Lamps.**—In addition to the incandescent lighting by single and grouped transformers, the Thomson-Houston Company have elaborated a very good system of street lighting by incandescent lamps which meets the demand for such public lighting over considerable districts in which it would not pay to put down transformers and work the incandescent lamps in parallel off the secondaries. This system of street lighting consists in running sets of incandescent lamps in series off the primary mains of the transformer circuits. A series circuit starts (*see* Fig. 114) from a point on one primary of the transformer circuit somewhere in the station, and carries a series of incandescent lamps. This line terminates somewhere or other on the other main primary, and as many of these series lines are run as may be necessary to fill up the district to be lit. The lamps used for this street system require a current of 3·5 amperes, and are of 20, 25, and 40 candle-power. The 25 candle-power lamp is largely used for street lighting. The socket used with the lamp is provided with a spring cut-out, similar to the Thomson Protective Device, the function of which is to keep the circuit closed in the event of the breakage of a lamp. The film is capable of standing the 25 volts required to work the

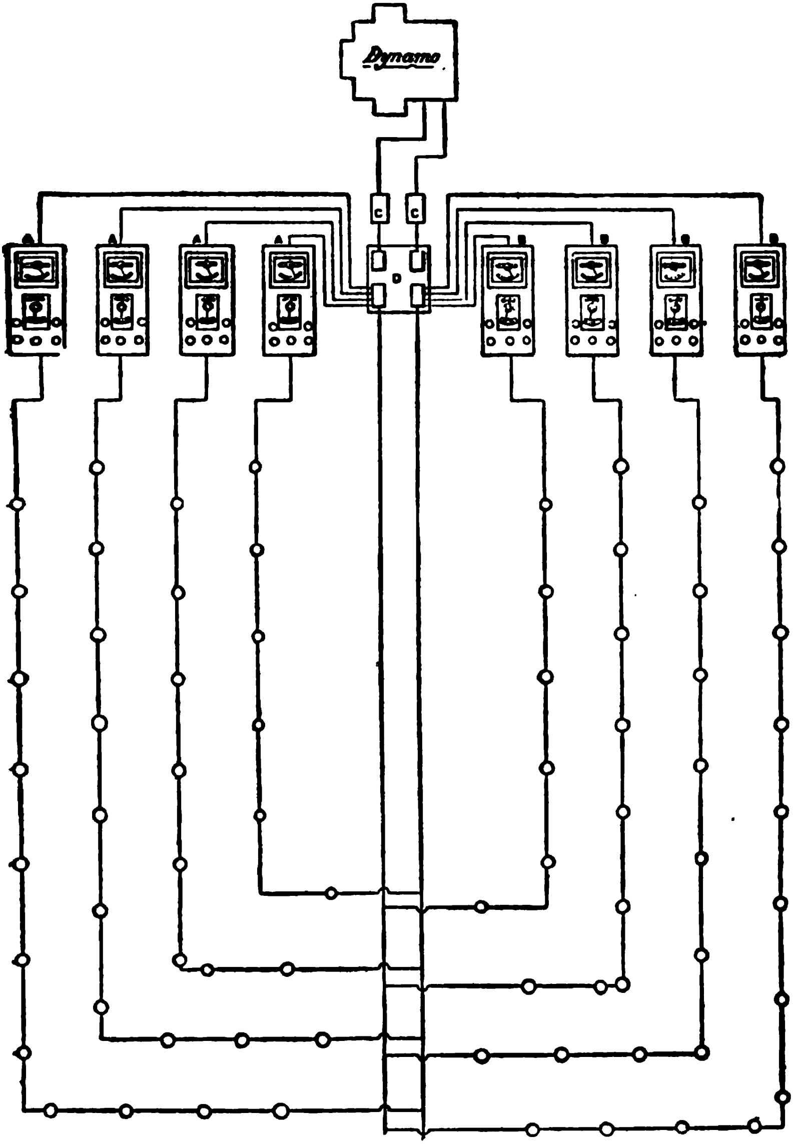


FIG. 114.—Street Lighting by Incandescent Lamps. Diagram No. 1, showing Street Lamp Circuits of 40 25 candle-power 25 volt Lamps, or 50 20 candle-power 20 volt Lamps.

lamp, but in the event of the lamp breaking the full pressure of 1,000 volts is thrown on the film, immediately breaking it through, and thereby short-circuiting that socket. This device proves itself in practice to be quick and efficient. In order to keep the current constant for each series line a current indicator is placed on each line in the station, and a switch by means of which one to five relief lamps may be thrown into the circuit. As long as the proper number (viz., 40) of lamps are burning on each series line the current indicator shows a current of 3·5 amperes, but if one lamp breaks or is extinguished the resistance of the circuit falls at once and the current rises. This is shown by the current indicator, and the attendant then switches on one or more relief lamps to restore the current to its proper value. When the broken lamp is replaced by the patrol the current again falls, and the relief lamp in the station is switched off. This series system may be worked by means of a constant potential alternator and primary lines merely for street lighting alone, but it is more frequently used in conjunction with transformer lighting. In this last case the constant potential primary lines are laid about in a district, and from these primaries are taken off not only the distributing conductors to supply the house transformers, but also the series lines for the street incandescents. The arrangement of circuits is then that shown in Fig. 115. Instead of employing the system of relief lamps and current indicator on a bank board, another device is employed sometimes, which consists in using a double socket and double lamps at each spot. One of these lamps only is in the circuit at one time; the circuit of the other is a branch in which is a film cut-out in series with the lamp. If its mate breaks, then the second lamp is automatically thrown into the circuit, and keeps a light alive at that place. There is in this case a relief lamp to every lamp, instead of merely five relief lamps in the station. In either case a system of transformer lighting for houses is combined with the street lighting, and the incandescent street lighting is specially applicable in the case of scattered villages and small towns or suburbs, where arc lighting would be impracticable. In connection with this system of street incandescent lighting, light trussed poles of iron are generally used, which carry the overhead series line and also the brackets for the street lamps (*see* Fig. 116). This system of street

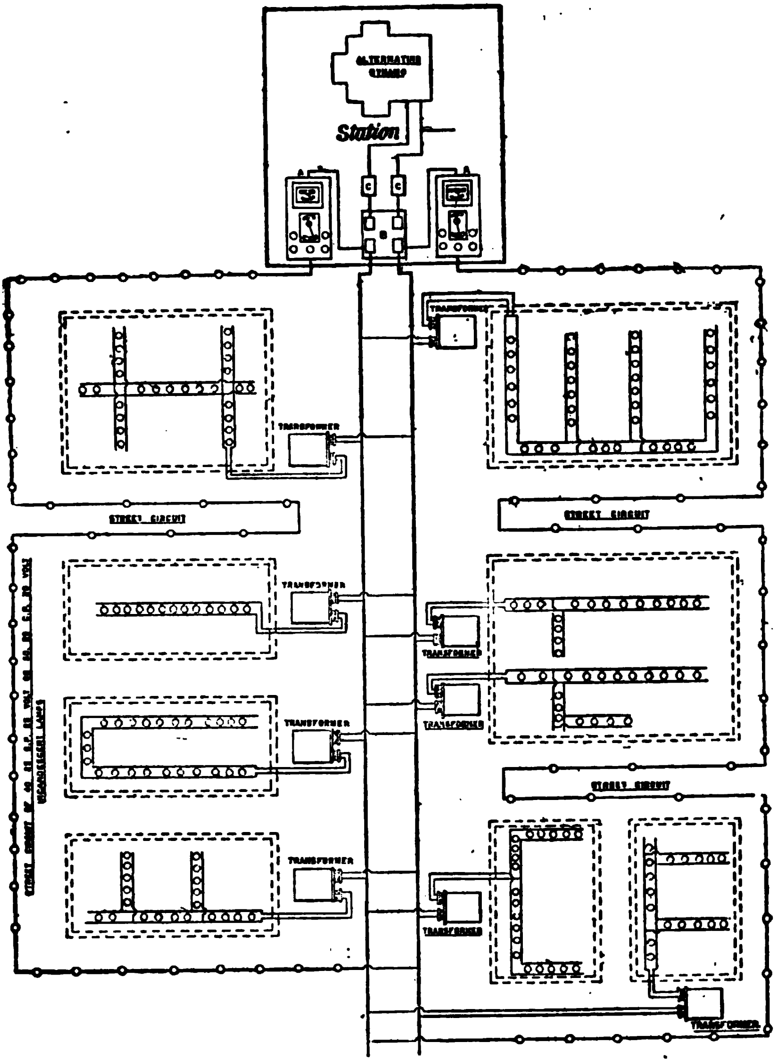


FIG. 115.—Street Lighting by Incandescent Lamps. Diagram No. 2, showing Street Lamp Circuits as arranged in connection with House-to-House Lighting with Transformers.

lighting is being considerably extended. In Malden, Mass., a suburb of Boston, U.S.A., a city of 20,000 inhabitants, street gas lamps have been entirely replaced by about 800 25 candle-power incandescent lamps on this system. The same system is in use at Newton (700 lamps) and Watertown, Mass.; West Point, Va.; Melbourne, Australia; Osaka, Japan; and many other places.

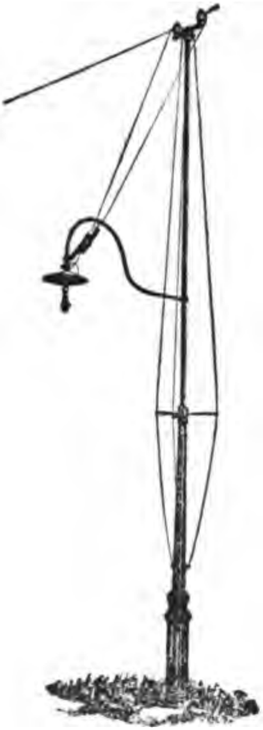


FIG. 116.—Light trussed Pole for Incandescent Street Lighting.

§ 28. Thomson-Houston Company's Central Stations. Salem Station. One of the most complete of the Central Electric Supply stations erected and equipped by the Thomson-Houston Company is that at Salem, Mass., U.S.A. Electric lighting began at Salem in 1881, by the erection of a very small arc-light plant, and has been several times remodelled and extended. Quite recently an unusually fine station for an output of 1,700 horse-power has been erected at Salem, and although arc lighting forms the bulk of the work done, yet as there is associated with it alternate-current machinery for incandescent lighting, it may properly be described here. In 1888 a site for the new station was selected close to water, and the erection of the station begun. The service of lighting was begun in September, 1888. At the beginning of 1890 the current was being supplied for 120 private arc lamps, 180 city arc lamps, 53 incandescent street lamps (series system) of 65 candle-power, 44 of 32 candle-power, and 2,000 of 20 candle-power. The arc-light dynamos are in number 11, of 30 lights each; the incandescent 2, of 400 lights each; 2 of 650 lights each, and 1 of 1,300 lights, and also current is supplied for 50 horse-power in motors. The details of the construction of the Peabody-street plant are as follows:—The station was designed by Mr. Henry C. Patterson, chief engineer of the Thomson-Houston Electric Company. In the construction of this station it was found necessary to drive about one thousand piles of oak and spruce. The piles are held firmly together by an immense bed of concrete made of Portland cement and broken stone two feet thick. On this bed the foundations for engines and shafting were constructed, which foundations are exclusively of granite laid in cement.

In equipping this plant it was thought advisable to install at first one-half of its present capacity. This was done by the erection of two compound condensing engines of 350 horse-power each, and one engine of 160 horse-power. All three engines belt to the same shaft (*see* Figs. 117 and 118), making it possible by the use of clutches to run any one of the engines on the same shaft at one time. In case of accident a defective engine can be shut down, and the load at once taken up by the others. Space is reserved, and foundations are already prepared, for two more engines of 350 horse-power each, and additional shafting. This makes the total output of the plant 1,660 horse-power. The engines are condensed by means of a surface condenser, which returns the condensed water directly back into the boilers, but passing on the way through economisers.

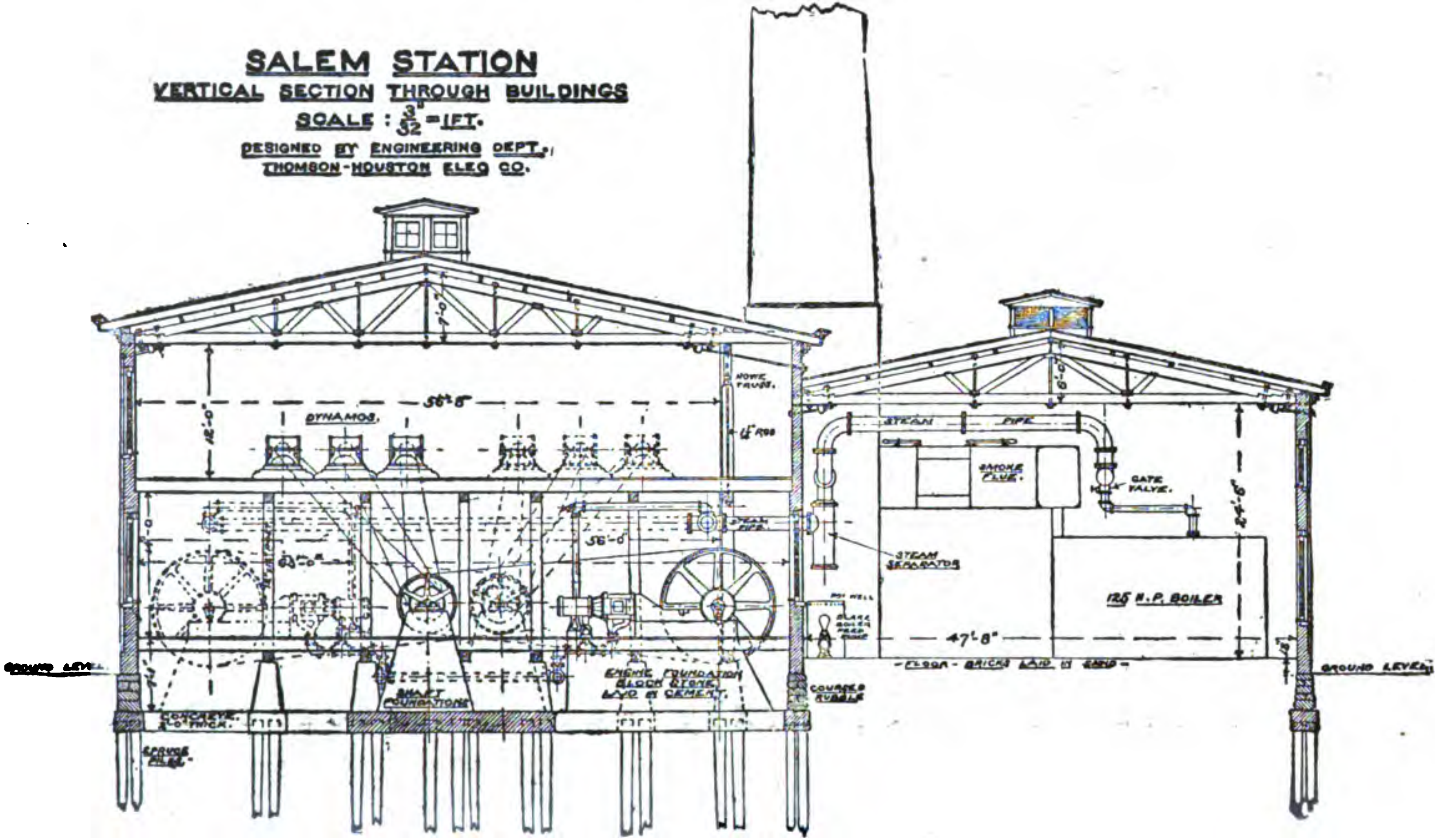

SALEM STATION
VERTICAL SECTION THROUGH BUILDINGS
SCALE : 3/32" = 1 FT.
DESIGNED BY ENGINEERING DEPT.,
THOMSON-HOUSTON ELEC. CO.
7'-0"
6'-0"
56'-8"
12'-0"
DYNAMOS.
HOWE TRUSS.
1½" ROD
STEAM PIPE
STEAM PIPE
SMOKE FLUE.
GATE VALVE.
24'-6"
56'-0"
STEAM SEPARATOR
HOT WELL
125 H.P. BOILER
47'-8"
GROUND LEVEL
FLOOR - BRICKS LAID IN SAND -
GROUND LEVEL
COURSED RUBBLE
ENGINE FOUNDATION BLOCK STONE LAID IN CEMENT.
SHAFT FOUNDATIONS
CONCRETE 2'-0" THICK.
SPRUCE PILES.

Fig. 117.

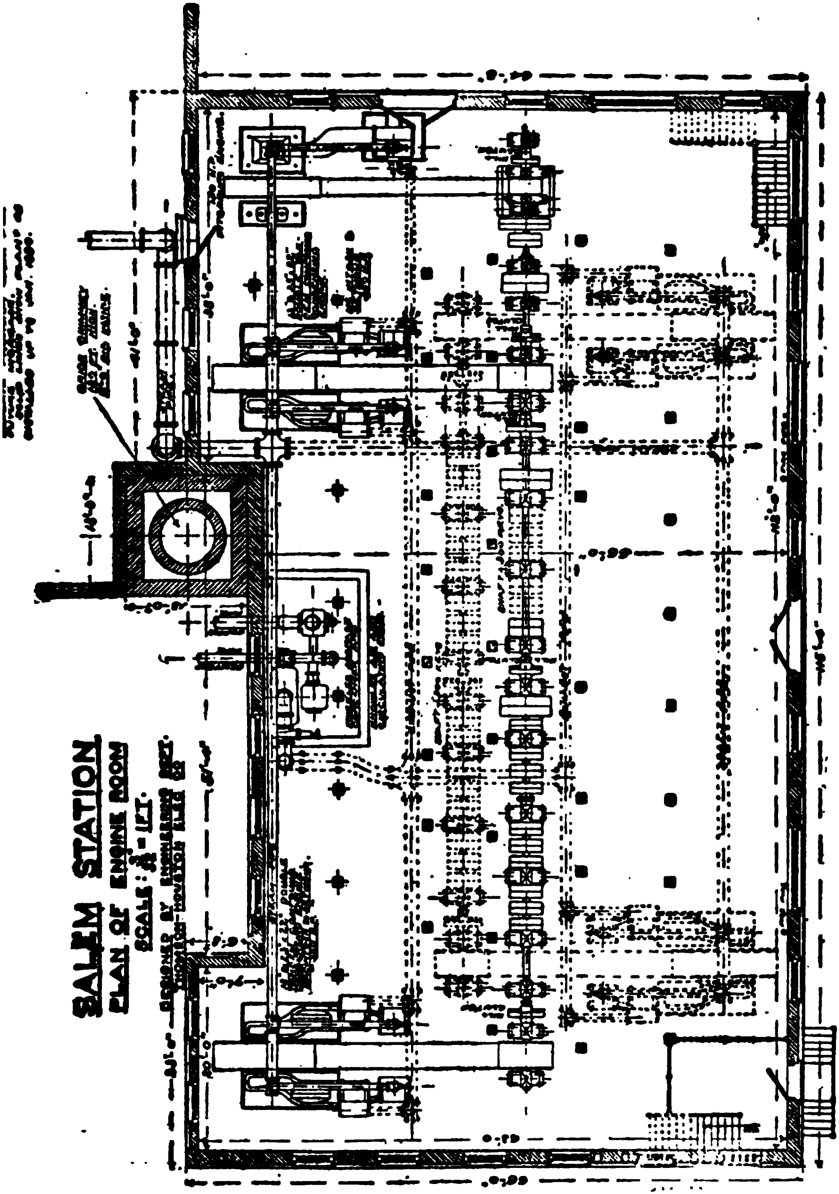

SALEM STATION
PLAN OF ENGINE ROOM
DESIGNED BY ENGINEERING DEPT.
THOMSON-HOUSTON ELEC. CO.

FIG. 118.

Figs. 117 and 118 show an elevation and plan of this Salem Station.

The boiler-house is 90ft. long by 50ft. wide; has space for ten boilers of 125 horse-power each, with Jarvis furnace, four of which are already installed. The boilers are placed upon granite foundations which rest upon piles, as in the previous case. They are constructed in the most approved manner, from specifications furnished by the engineering department of the Thomson-Houston Electric Company. They are of the ordinary tubular type, 72in. in diameter and 17ft. long, made with extra strong seams and steel tubes, braced in a thorough manner, and having a working pressure of 125lb. to the square inch. The piping of this plant has been carried out with consideration for future output of 1,660 horse-power, and all main steam pipes, as well as exhaust pipes, are large enough for this full duty.

The second floor of the main building, which is 115ft. by 66ft., is utilised for machines with a capacity of forty-five Thomson-Houston dynamos, fifteen of which were installed at once. The remainder of the second floor, not used for this purpose, is divided into offices, work-rooms, testing-rooms, toilet-rooms, &c. The coal shed has a capacity for 2,000 tons.

The brick chimney of this plant is 130ft. high, and 13ft. square at the base. The chimney is square in form, with a round core 72in. in diameter at the bottom, and 76in. in diameter at the top. The structure contains 250,000 hard bricks laid in cement, and also 41 perch of granite in the foundations, which rest on 60 oak piles firmly bound together by 3ft. of Portland concrete. This chimney has a capacity for 1,500 horse-power.

The entire work of construction, the building, and the placing of the engines, boilers, and machinery was carried out under the direct supervision of Mr. Patterson. In the construction of this plant, it has been Mr. Patterson's endeavour to construct one of the most economical and best running stations possible, and also of an original design. As the Salem Company had increased their plant twice before the construction of this plant, it was their desire to build one of such magnitude as to be entirely sufficient for the future; and as at present they are exerting about 600 horse-power, it would seem that there is ample in reserve for some time to come. Believing that in the construction of an electric light station the best is the cheapest, and that a station should be attractive to the employés, the Salem Company has provided all necessary accommodation for them with the later addition of a library, which is filled with recent electrical books and periodicals entirely at the disposal of the employés.

In regard to the economy of the steam plant, the change from high pressure to compound condensing, in their present location, has been highly satisfactory, the average coal bills have been reduced 50 per cent. since getting the new station into successful operation. This is due to better facilities for getting coal, as also to the more economical engines. At a recent preliminary test made with Georgia Creek Cumberland Coal and steam pressure at 110 pounds, the boilers showed an evaporative power of 9·7 pounds of water per pound of combustible. The engines, which were developing a variable load, from 192 to 419 horse-power, showed an economy of 1·8 pounds of coal per horse-power per hour.

§ 29. The Brush Alternating Current System.—Mordey Alternators and Transformers.—A very complete alternating current system has been developed by Mr. W. M. Mordey, and the construction of his alternators and transformers is carried on by the Brush Electrical Engineering Corporation of London.

The Mordey Alternator is a wide departure in construction from the usual forms of alternating current machines, and presents several features of great interest. This alternator is of the type in which the armature coils are stationary, while the field magnets revolve. The general form of the alternator is represented in Fig. 119. The armature coils consist of a series of thin copper strips, wound over a central core of non-conducting material, such as slate or porcelain. These armature coils are fixed in the interior of a ring frame projecting inwards in a radial manner, and supporting one another by being placed in close contact. Each coil can, however, be removed separately for repairs, and the coils when in place are joined up in series (*see* Fig. 120). The field magnet consists of a central shaft, which is embraced by a magnetising coil (*see* Fig. 121). On to the alternator shaft is fixed a pair of cast iron pole-pieces, which consist of a series of cast iron fingers meeting together with a small air-space between the extremities. It is easily seen that the action of the magnetising coil is to make all the magnetic poles of one side, say, north

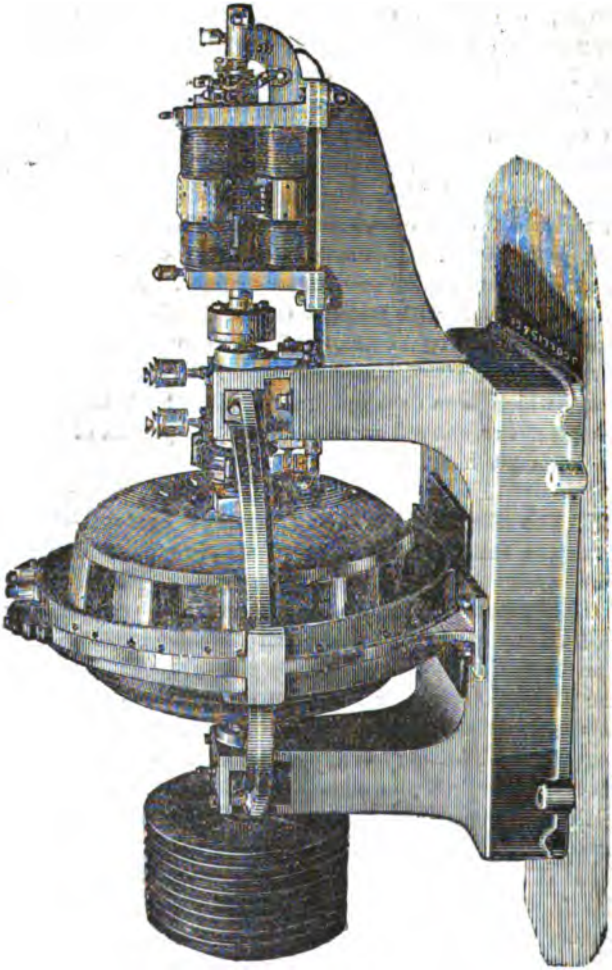


FIG. 119.—Mordey Alternator.

poles, and all on the other side south poles. There is, therefore, no magnetic leakage between adjacent field poles on the same side, and in this respect the machine differs strikingly from all ordinary types of alternators. This revolving field magnet is so adjusted in the machine frame with respect to the armature ring that, when rotating, the poles of opposite sides come in close contiguity to the radial armature coils; hence, as the field magnet revolves, a series of bunches of lines

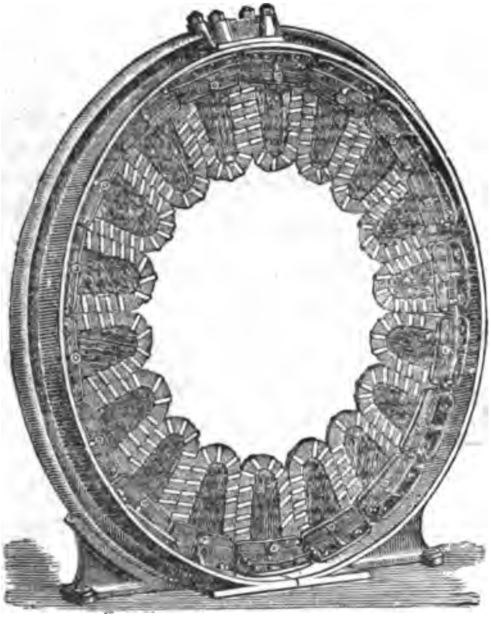


FIG. 120.—Armature of Mordey Alternator.

of magnetic force sweep laterally through each coil, which is equivalent to moving each coil sideways through an intermittent but intense magnetic field. Referring again to the figure of the armature, it may be stated that the armature coils are formed of copper ribbon, about $\frac{7}{16}$th of an inch wide; each coil is bolted on to the ring frame by brackets, and the ends of the strip conductors brought out through porcelain insulators. These brackets are so bolted to the gun-metal supporting ring that they can be removed without dismounting the machine. The coils, as stated, stand in the narrow space between the poles of the field magnet. The poles of the field magnets are covered externally with a metal shield of a saucer shape, which prevents needless churning of the air. On the shafts of the field magnet are a pair of contact rings with rubbing contact, by which the exciting current is conveyed to the bobbins of the field magnet. The shaft is constructed with a collar like the thrust bearings of a steamship screw shaft, by which any lateral shake of the magnet is prevented. The bearings are oiled by means of an automatic oil-circulating arrangement in the larger sizes of alternators, which consists of a small force pump drawing oil from a reservoir and forcing it through the bearings.

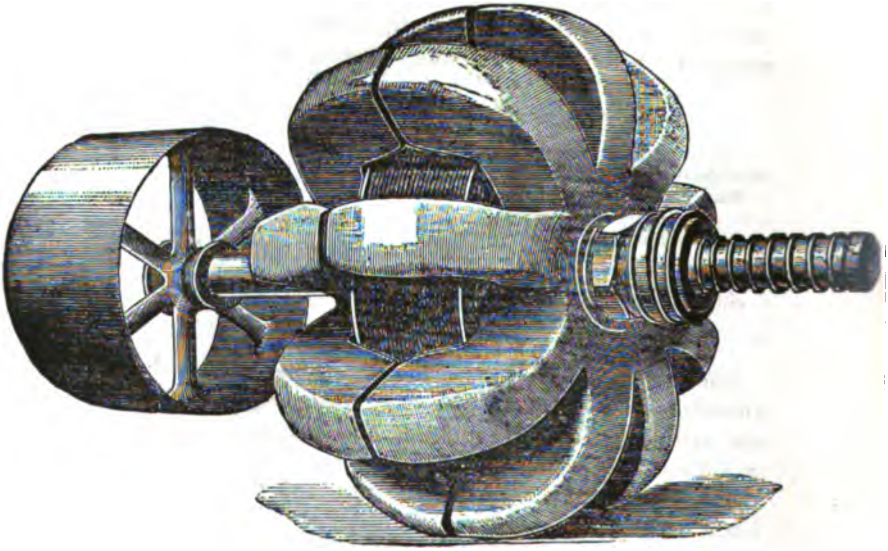


Fig. 121.—Field Magnet of Mordey Alternator.

From one pair of coils wires are taken off, by means of which the electromotive force of the machine is measured. In the 75-unit machine there are 24 armature coils, and hence the reading of the voltmeter is $\frac{1}{24}$th part of the full pressure of the machine. Owing to the low armature resistance, the machine has very great self-regulation for various loads. The characteristic curve of the 37½-unit machine is shown in Fig. 122, by which it may be seen how small a drop in electromotive force takes place between full and no load. These machines are usually constructed for electromotive force of 2,000 volts. The energy taken up in magnetising the field is under two per cent. of the full output of the machine. The exciting current is either provided from a small direct current machine, fixed to the frame of the alternator, and driven from the same shaft; or, generally, in central stations, by means of separately driven exciters. These dynamos are constructed in the following sizes:—

Sizes of Mordey Alternators.

Manufacturers' Mark	A. 7.	A. 9.	A. 10.	A. 12.	A. 14.	A. 15.	A. 20.	A. 40.
Output in kilowatts	25	37·5	50	75	100	150	200	400
Revolutions per minute	857	666	600	500	428	400	300	150

The periodicity selected for these machines is 100 complete alternations per second. The most frequently used sizes are the A. 9, which is a 37½-unit machine, and the A. 12, which is a 75-unit machine. The first is capable of maintaining about 600 16 c.p. incandescent lamps, and the A. 12 about 1,200. The most interesting quality of these dynamos is the great perfection with which they work together in parallel on the same circuits, and when once brought into step with one another by means of synchronising arrangements, as explained in a previous section. It is impossible to break these machines out of step with one another when once so synchronised, and they run perfectly in parallel for any load downwards from full load to that of a single lamp. The construction of these alternators marked a distinct epoch in the development of alternating current apparatus, and the Paper read before the Institution of Electrical Engineers, in 1888, by Mr. Mordey, was followed by a demonstration of the practicability of working these machines in parallel, not only when they were generating equal electromotive forces, but when one machine was giving 1,000 volts and the other 2,000. A small adjustable resistance is sometimes used in connection with each machine to regulate within small limits the electromotive force, but it is not found necessary to provide any automatic means of regulation in consequence of the low resistance of the alternator armature.

Mr. Mordey claims for these machines, not only that they have a very low resistance, but a very low armature self-induction. The armature resistance of the 37-unit machine

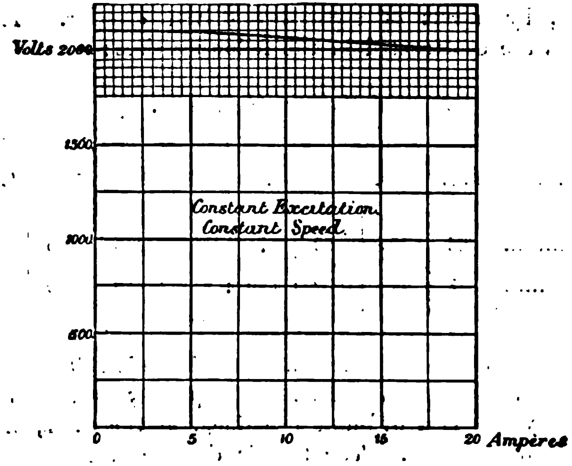


FIG. 122.—Characteristic Curve of Mordey Alternator.

is stated to be about 3 ohms, and the mean coefficient of self-induction about ·03 henry.

The Brush Corporation have designed, also, a compound high-speed engine specially adapted for driving these alternators. The smaller sizes of these engines are employed for driving direct the exciters in central stations, the larger sizes for driving the alternators by means of a single rope gear. The speeds of these engines vary from 120 to 250, and are, in all cases, placed high enough to give a steady current from the dynamo. This is an important point, especially with alternators designed to run in synchronism. The crank shaft and motion rods are entirely of Siemens steel, and the motion bearings square-seated to allow of easy adjustability to original level. The engine is of the inverted marine type, having a solid back frame.

The high-pressure cylinder is fitted with a piston valve and the low-pressure cylinder with a slide valve. The steam admission and speed of the engine is controlled in three ways, according to the size of the engine and the conditions under which it is to work.—

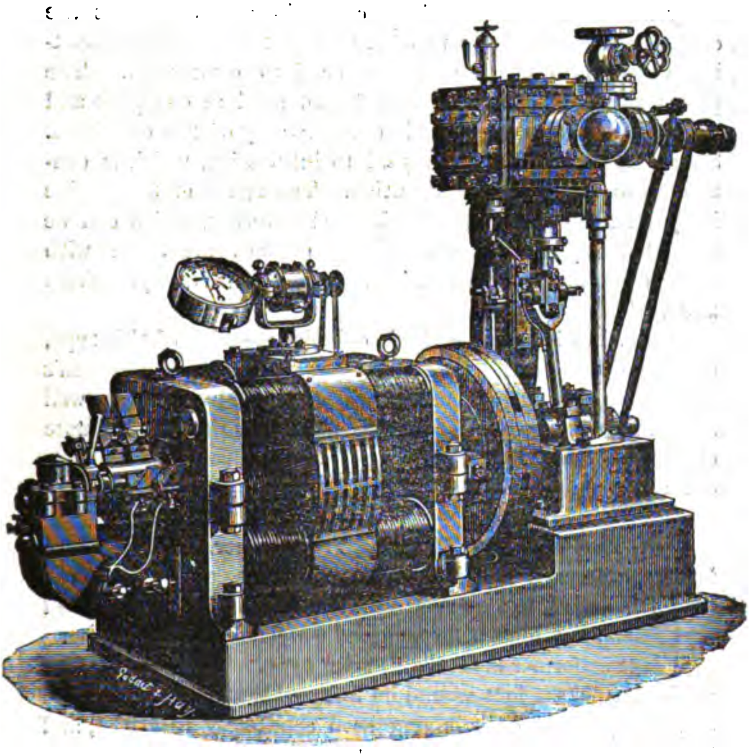


FIG. 123.—Direct-driven Exciter for Mordey Alternator.

1st. By an Acme governor and throttle valve, adjustable by hand while the engine is running.

2nd. By an Acme governor and throttle valve, supplemented by hand-regulating expansion gear acting on both valves.

3rd. By automatic expansion gear, acting direct on the high-pressure valve, adjustable by hand whilst working, supplemented by a hand regulation of the low-pressure valve.

By means of either of these controlling arrangements the engines can be regulated to work well and efficiently, exhausting either into the atmosphere or into condensers. The piston rods and cross-heads are forged solid in one piece and move in a guide which holds one side only of the crosshead. Special attention has been paid to lubrication, which is continuous and needs little attention. The speed of the engine is governed by a sensitive high-speed governor, which can be regulated whilst in work. These engines are made with strokes varying from 4 to 24 inches, and speeds varying from 250 to 600.

In Fig. 123 is shown a single cylinder machine of this type, coupled direct to a Victoria dynamo by means of Raworth's flexible friction grip coupler. Such a combination is well adapted as an exciter for central station work; two or more of these exciters can be arranged to feed the field magnets of a series of alternators.

§ 30. The Mordey Victoria Transformer.—These transformers are of a very simple form, the points aimed at in the design being as follows:—High efficiency at all loads; good regulation; and high insulation and convenience in handling.

This transformer is of the "shell" type. The high and low pressure coils are first wound on formers in a lathe. The high and low pressure coils having been separately insulated, and insulated from one another, are then enclosed in an iron core made of sheet iron stampings. A rectangular sheet of iron has a rectangular hole punched out of it to such a size that the piece punched out when placed cross-wise (*see* Fig. 124) serves as a core. These rectangular frames and cross-pieces are piled up in and around the primary and secondary coils, the rectangular frame being slipped over the coil and the cross-piece put through the coil, each plate being separated from its neighbour by thin paper, and the whole pile of plates then compressed together by means of tie rods in a cast iron frame. The finished transformer is then enclosed in an external iron case (*see* Fig. 125). This iron case may be made to contain also double pole high tension safety fuses and switches, and is then adapted for being placed on customers' premises. The transformers are made in thirteen standard sizes, varying from 750 to 36,000 watts, and all are thoroughly tested and have a long continued run at full load before being sent out. In constructing this transformer, Mr. Mordey's aim has been to design a transformer having not only high efficiency at full load, but high efficiency at lower loads. The following values are given by him, as results of experiments made with a 6,000 watt transformer.

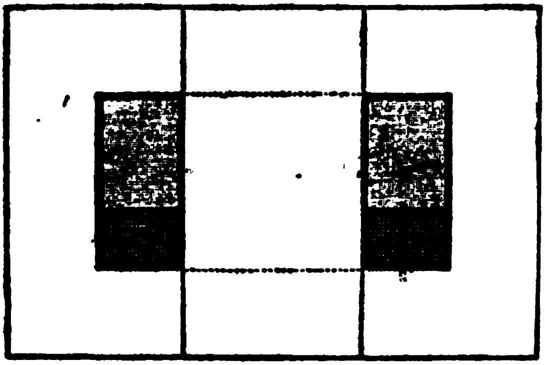


FIG. 124.—Stamped Sheet-iron Disc for Mordey Transformer.

Efficiency of a Mordey Transformer.

	Efficiency.
Full load	96·7 per cent.
¾ load....................................	96·2 ,,
½ ,, ...	95·1 ,,
¼ ,, ...	92·1 ,,
⅛ ,, ...	86·7 ,,
No load	Loss 1·8 ,,

The larger sizes of transformers are slightly more efficient than the above, especially at small load; the smaller sizes, on the other hand, are slightly less efficient.

This form of transformer is very easily repaired, and at the

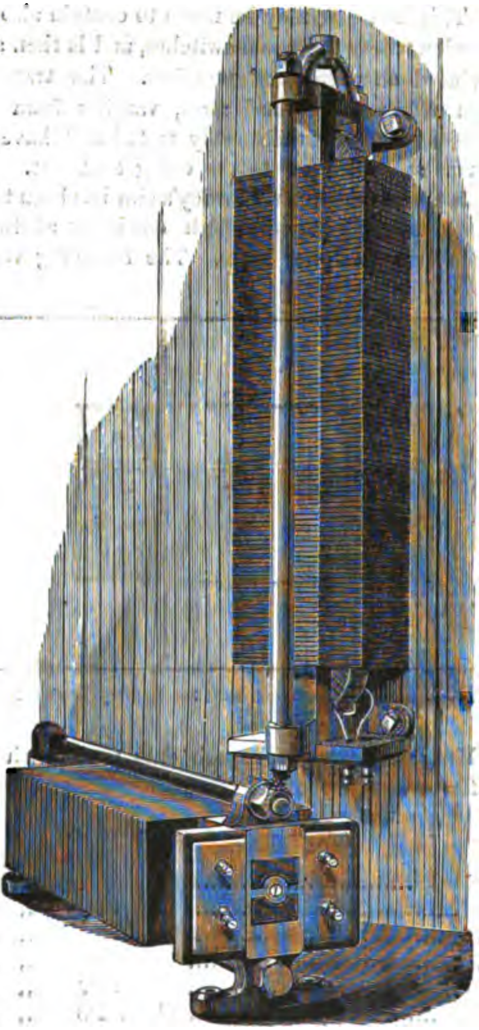


Fig. 125.—Mordey Transformer.

same time has a very small electrostatic capacity, and a very small "drop" due to magnetic leakage.

§ 31. High Tension Switches and Fuses.—Other details in connection with this alternating current system have been carefully worked out.

A high tension switch has been perfected which has the following qualities:—

1. A long break.
2. A quick break.
3. Good contact.
4. Complete insulation from the hand of the operator.

It consists of a hinged arm, kept normally out of contact with a copper jaw by means of a spiral spring. It is closed by pulling a silk or cotton cord, which may be any length. By pulling the cord, the arm is brought into contact with the copper jaw, where it is retained by a catch or trigger. It is released by pulling another cord, so that neither in breaking nor in making contact is there the least danger of shock to the user.

In the standard switchboard for central station purposes the high-tension switches are entirely enclosed, and are worked by external handles and cords, as described. High-tension safety cut-outs have been perfected for use with these machines. It has been demonstrated practically in many cases that safety fuses of very considerable length are unable to break the arc produced by a short circuit in the mains when the current is being supplied from a dynamo of very low resistance and inductance. The fuse adopted by the Brush Corporation consists of a copper wire, about three inches in length, enclosed in a glass tube, filled in with a non-conducting and non-inflammable powder, which entirely quenches the arc when the fuse wire melts. These fuses are comparatively inexpensive, and are so small that they can be put with safety inside the smallest transformers, thus avoiding the necessity for separate fuse cases.

§ 32. Alternating Current Stations on the Mordey System. Lynmouth Central Station.—An interesting installation has been erected at Lynmouth, employing these Mordey alternators. This station is a water-power station, the power being obtained from the River Lyn. The water of the river is diverted into an open conduit and thence into an iron pipe,

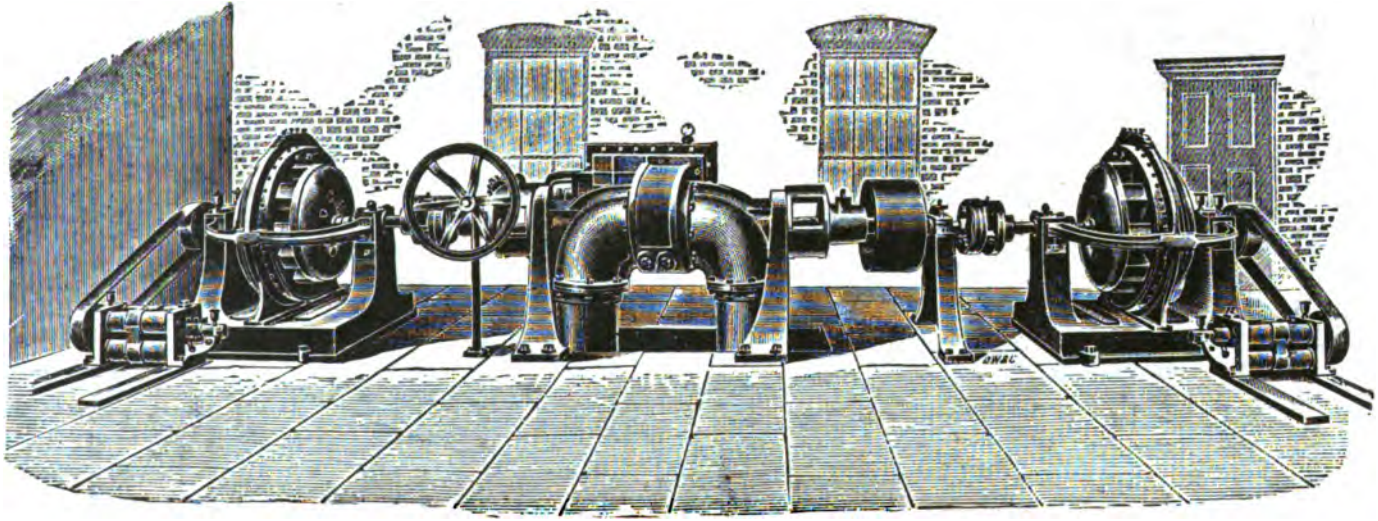
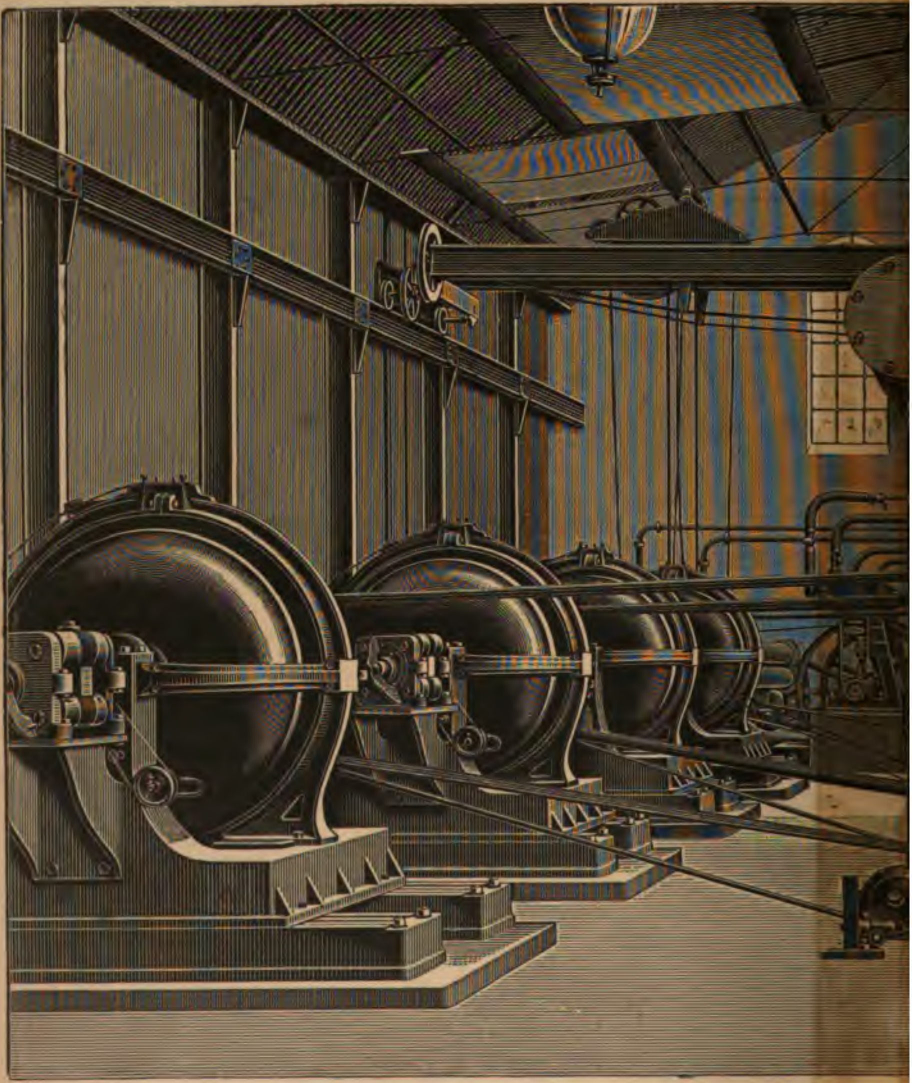


FIG. 126.—Lynmouth Alternating Current Station.

30in. in diameter and 1,705ft. in length, the available fall of water being 95ft. This fall of water is conducted to a 14-inch turbine, capable of yielding 200 H.P., the water being returned to the river when it has done its work. The horizontal shaft of the turbine is coupled direct to two Mordey alternators of the 37½-unit size, running at 650 revolutions per minute. The exciting current is furnished from two small direct-current Victoria machines belted on to the shafts of the alternators (*see* Fig. 126). The current is supplied from the alternators at a pressure of 2,000 volts, partly by underground and partly by overhead mains. From the station it is conveyed to Lynton, where the distribution takes place, through transformers placed on customers' premises. The primary mains in the town are underground, and the pressure is reduced from 2,000 to 100 volts for use in incandescent lamps by transformers on the various premises. Each of the 37½-unit alternators employed is capable of maintaining 1,200 or 1,300 8 c.p. lamps, all burning at one time. The plant has now been in operation some years most successfully.

§ 33. **Bath Electric Lighting Station.**—The electric lighting of Bath is carried out by means of alternate-current plant, on the Mordey-Brush system. The incandescent lighting plant and the bulk of the generating plant was constructed by the Brush Company and erected to the instructions of Mr. Massingham, who commenced electric lighting work there in the first instance as a private enterprise. The station is a brick and stone building, covering an area of about 150ft. by 90ft. The engine and dynamo room is 113ft. by 40ft. The walls are of stone, having vertical iron pillars at intervals, which carry a horizontal girder on which an overhead traveller runs. The boiler-house is 90ft. by 40ft., and lies adjacent to the engine-room. At one end of the boiler-room is a red brick chimney shaft, 90ft. high and 4ft. 9in. clear diameter at the top. This shaft takes the products of combustion from four Babcock boilers of 150 H.P. each. Room is provided in the house for twelve such boilers. The engine-room (as shown in our engraving) is occupied partly by a Thomson-Houston arc-light plant and partly by the alternate-current plant. This last consists of four 75-unit Mordey alternators. Each alternator is driven by rope gearing from a separate high-speed compound condensing engine of 150 H.P., built by the Brush Company. Each alternator has its own exciter driven from the alternator shaft. The voltage of the alternators is 2,000, and the maximum current from each 35 amperes. Each of these dynamos is driven by a continuous length of 1¼in. cotton rope, running eight times round the pulley of the alternator and the grooved fly-wheel of the corresponding engine, a guide pulley serving to keep the rope in place in bringing it back from the last groove to the first. The diameter of the engine cylinders is respectively 12in. and 20in., and the stroke 14in.. There are special arrangements for altering the cut-off by hand whilst the engine is running. The engine speed is 180 revolutions per minute. The engines exhaust into a 14in. common exhaust, and arrangements are made to lead the exhaust steam into condensers, or into the atmosphere. The condensing plant consists of two surface condensers, each having 1,000 square feet surface, and one Raworth combined circulating and feed pump, which is driven by a compound engine. The object of this last arrangement is to obtain greater economy in the power used in driving the circulating and feed pumps. Water for condensing is available from the river close to which the station is situated. Valves are fitted to the condensers, so that one or both can be used at the same time, and a relief valve is fitted into the end of the exhaust pipe, so that in the event of a condenser being shut off exhaust takes place automatically into the atmosphere. A 3-inch feed pipe runs from the condensers to the boilers, and, in addition, Duplex pumps have been fixed, so that the boilers can be fed independently of the condensers. For draining the steam pipe two automatic steam taps have been fixed; these discharge into a tank from which the water flows into a hot well. The alternators work in parallel, and deliver currents into eight circuits, which are laid underground. These high-pressure conductors consist of Callender cable, laid under the footways, in iron troughs, filled in "solid" with bitumen. These cables have proved themselves to be satisfactory as regards insulation. In each house or building lighted there are placed transformers in iron cases, and these are fed with primary current at 2,000 volts. They reduce



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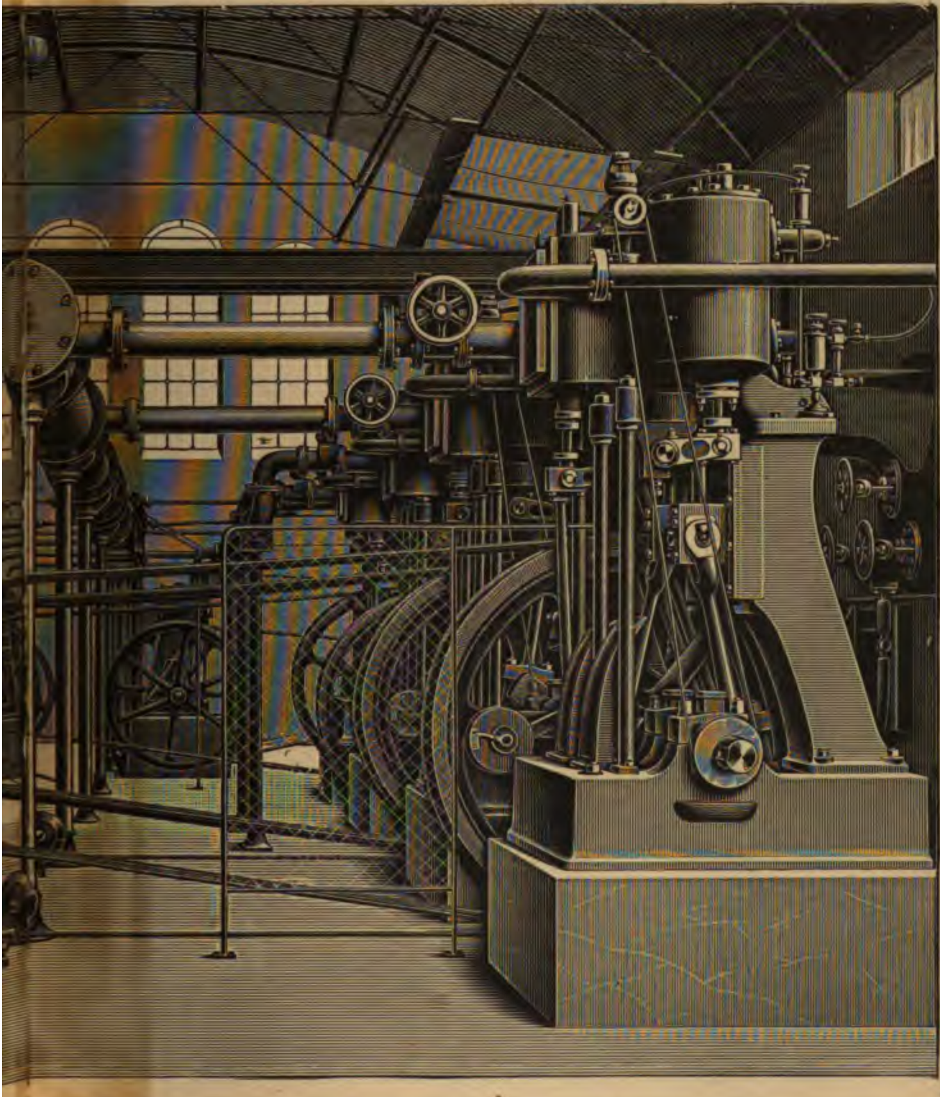
THE BATH ELECTRIC LIGHT CENTRAL S

ENT TRANSFORMER"—VOL. II.



AL STATION (referred to on pages 301—303).

the pressure to 100 or 50 volts for use with incandescent lamps. As the distances to be covered were considerable, and the ighting at first sparse, it was found necessary to employ the distributing transformer system, and not to "bank" the transormers. The sizes of transformers chiefly used are the 750, ,500, and 3,000-watt sizes. These transformers are of the mproved Mordey type, above described. A very similar station was also erected at Bournemouth by the Brush Company for the supply of electric current on the alternating system. Mordey alternators, Brush compound engines, and Babcock boilers are also employed there. The Mordey alternators are worked regularly in parallel.

§ 34. **Ferranti Alternating-Current System.**—Mr. Ferranti began in the latter part of 1885 to develop his alternating-current system, comprising alternators, transformers and cables of special forms, constituting together a complete system of alternating-current supply by means of transformers. We proceed to describe the several elements of this system and then some of the complete installations which have been made with it.

The Ferranti Alternators.—The general design of one of these alternators is shown in Fig. 127. The revolving portion is the armature in which the alternating currents are generated, and in the case of the direct-driven alternators this armature constitutes the fly-wheel of the engine. The fixed portion is the field magnet. The general construction of the dynamo is seen to consist of a frame in two portions, which are bolted together, but which can be separated from one another along one of two planes, for the purposes of repairing and cleaning (*see* Fig. 128). Each half of the cast-iron frame, or carcase, carries a series of projecting wrought-iron pole-pieces, which are cast into the frame (*see* Fig. 129). These pole-pieces come into opposition with one another when the frame is put together, and are excited by magnetising coils, consisting of copper strip, wire, or band, wound on them, the different layers being insulated by thin sheet vulcanised fibre. When these pole-pieces are magnetically excited, the poles are alternately north and south all round the frame on one side, and in opposition to each north pole in one half of the frame

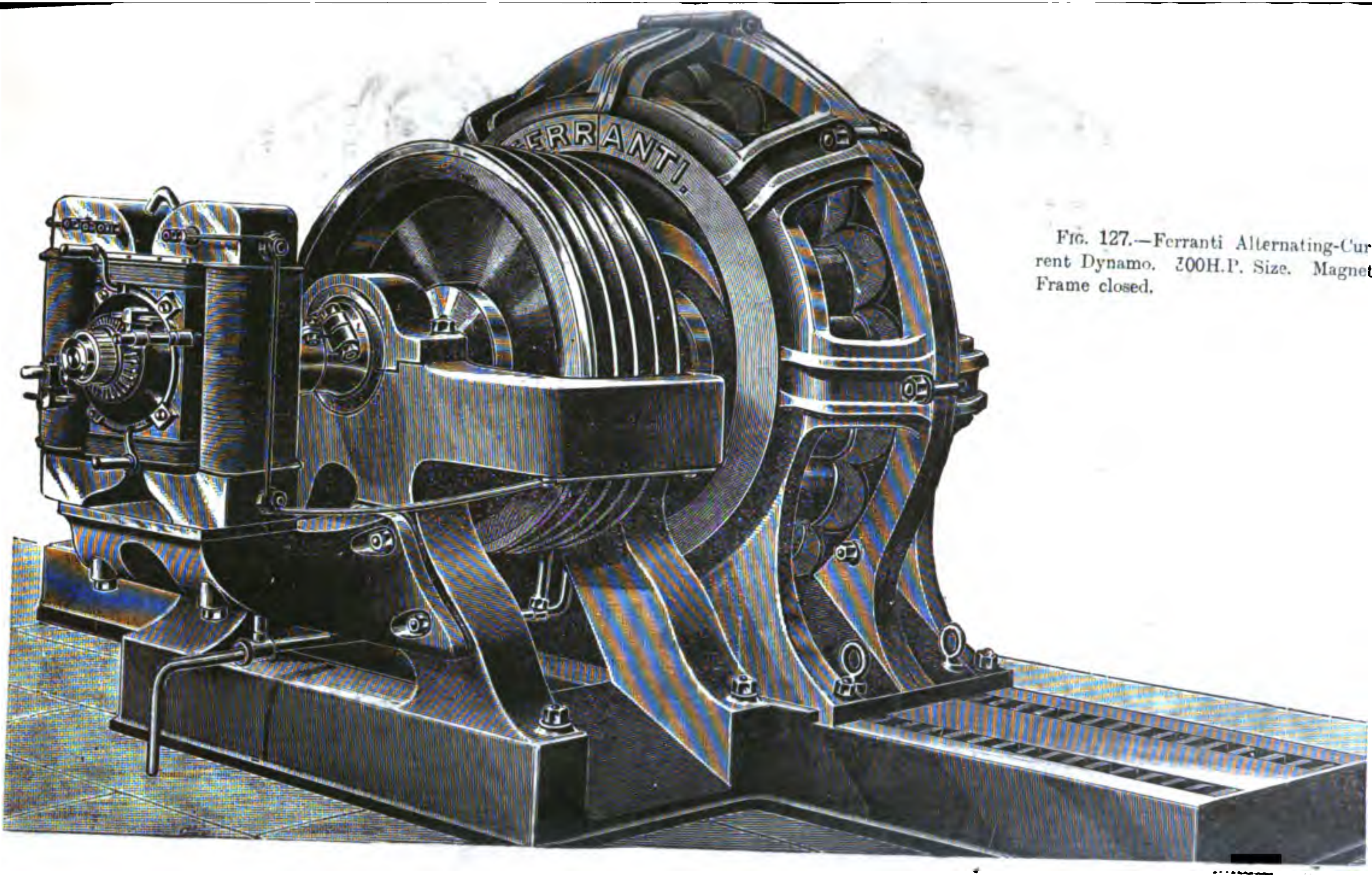


FIG. 127.—Ferranti Alternating-Current Dynamo. 300H.P. Size. Magnet Frame closed.

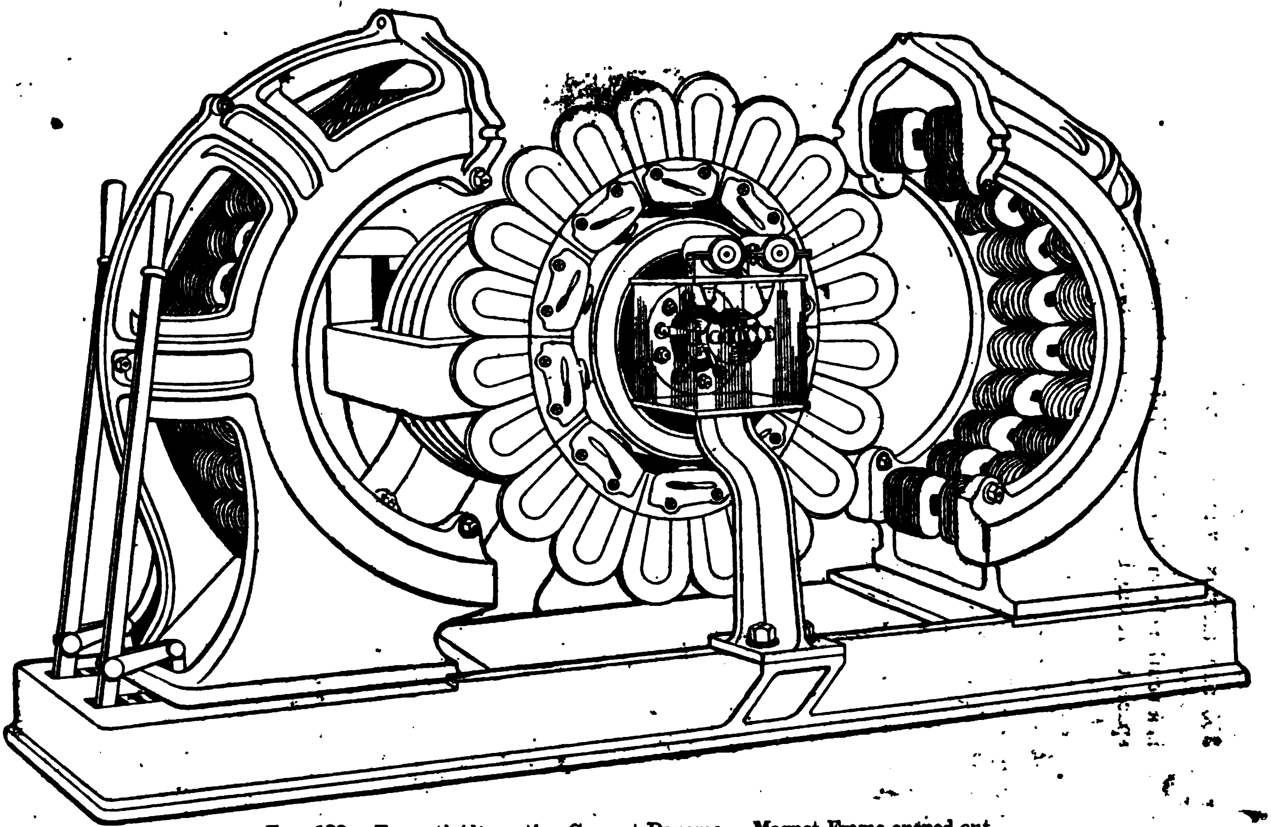


FIG. 128.—Ferranti Alternating-Current Dynamo. Magnet Frame opened out.

is a south pole on the other half of the frame. In the clearance space, therefore, between the poles there are a series of bunches of lines of force alternately in opposite directions, and there is also a leakage field between the adjacent oppositely named poles on the same side. The armature shaft is a steel shaft having

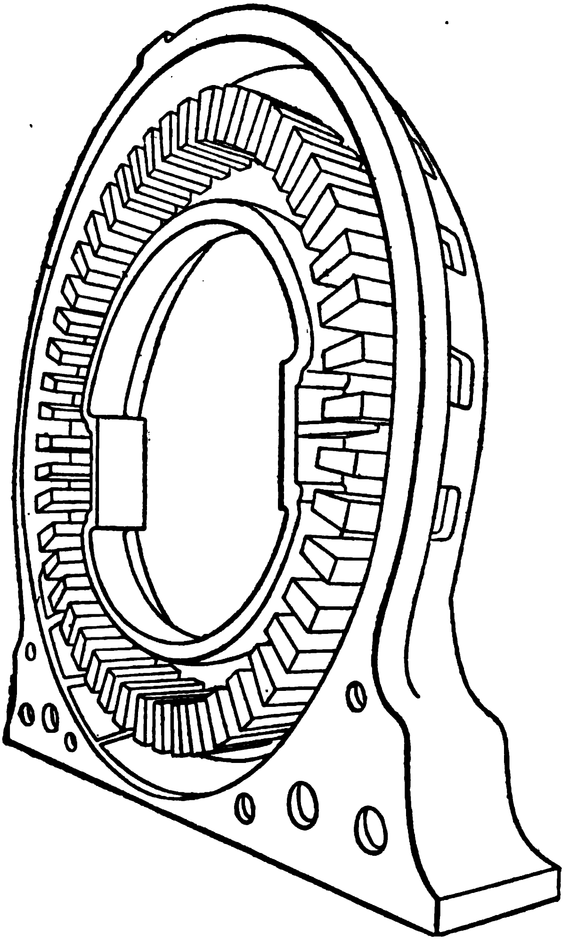


FIG. 129.—Half-Carcase or Magnet Frame of 1,250 H.P. Ferranti Alternator at Deptford.

a grooved pulley keyed on it for rope driving, which is slung between two self-adjusting bearings. The steel shaft carries a gun-metal hub, or disc, which forms the basis of support for the armature coils. The armature winding has been developed from what used to be known as the zigzag armature winding, and is indicated as to its general nature by the diagram given in Fig. 130. Opposite to each magnetic pole stands one loop of the armature, and as the armature moves forward in the alternating field induction takes place in each loop in such a way that the currents induced in the loops are all in one direction during one step of the progress from pole to pole, and all in the other direction during the next successive step. The machines, therefore, yield an alternating current, the frequency of which is given by the product of half the number of pole-pieces and the speed of revolution. This frequency is now in all machines 10,000 semi-alternations per minute, or 5,000 complete alternations, equivalent to a frequency of 83 ∿ per second. In the actual machines, the various portions of the armature consist of a set of separate flat spirals of copper tape, wound up into flat, oval, or egg-shape coils on a non-conducting core of a particular kind. A pair of these coils are so joined up that when their outside ends are connected together in the centre, the course of the winding in the two coils, looked at from one side, is in the opposite direction. This pair of coils constitute one unit of the armature, and they are carried on insulated metal bases, called bobbin-holders, as shown in Fig. 131. Each armature coil consists of

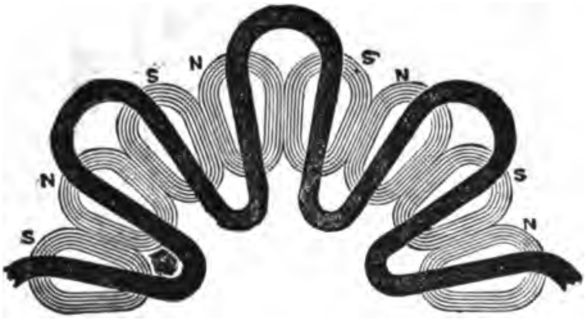


FIG. 130.—Ferranti-Thomson Armature Winding.

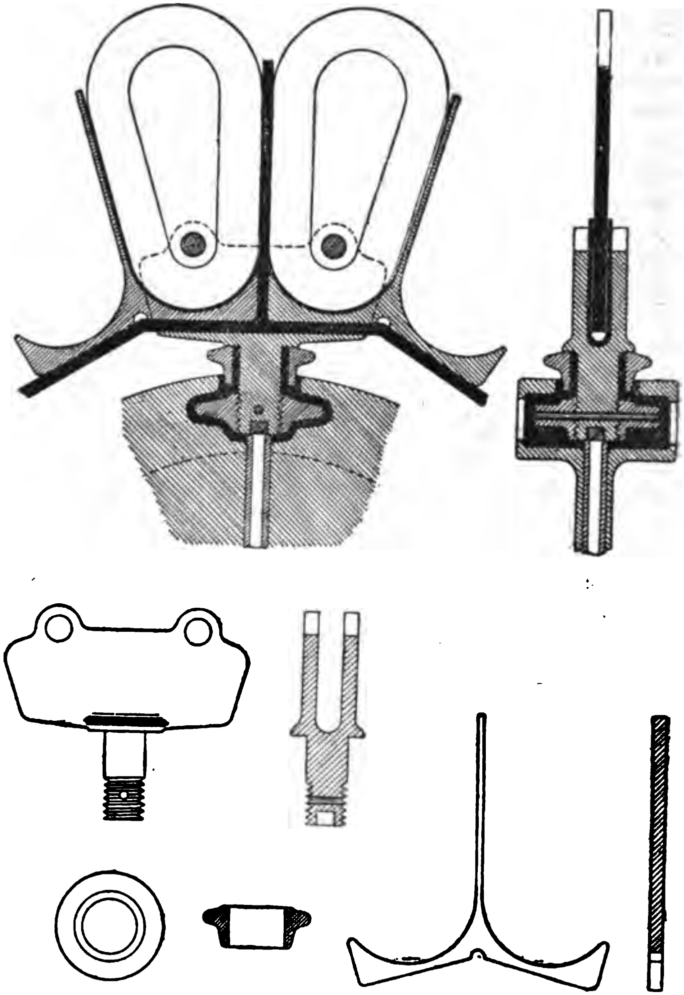


FIG. 131.—Details of Armature Bobbins and Bobbin Holders of Ferranti Alternator.

high-conductivity copper tape, which has a groove or depression impressed upon it, in order that when wound up into a flat spiral, the different layers of tape shall not slip over one another. The insulating material between the layers of copper tape consists of one or more strips of thin and well dried vulcanised fibre. The core on which this spiral is wound up consists of a laminated brass piece cut into fingers or blades, like a fan; the interval between these fingers is filled up with asbestos cardboard, and the whole mass is compressed very tightly into a stiff non-conducting core, on which the corrugated copper tape is wound. When these bobbins are thus prepared, they are soldered together in pairs, as described, the one individual of the pair being held in one bobbin-holder and the other in the adjacent one. The two bobbins which are held in the same bobbin-holder are insulated from each other by a strip of ebonite put between them, but the ends of the copper tape on the two coils are connected together electrically through the bobbin-holder. The shanks of the bobbin-holders are fixed into the gun-metal hub of the armature by an insulating cement made of sulphur, and the shank of the bobbin-holder is protected by an insulator of ebonite formed with wide flanges so as to give great surface and prevent electrical leakage. The general method of fixing these bobbin-holders is as follows:—In the gun-metal hub there are a series of cavities. The shank of the bobbin-holder is passed through the ebonite sleeve insulator and down through a hole in the periphery of the hub. A nut is then screwed on its end, which nut lies in the cavity in the hub. The space all round the nut in the cavity is then filled in with the sulphur cement. This method of insulating and holding the bobbin-holders has been found to be electrically and mechanically an excellent one.

When the coils are all arranged in the armature, they are connected up in two parallel series, so that one end of the diameter constitutes one pole of the machine and the other end the other; connections are made with these two extremities of the armature circuit by means of insulated copper rods, which come out through the hollow steel shaft to collector rings fixed to this shaft (*see* Fig. 132). When the armature is in place, these thin bobbins move round in the narrow air space between opposing field magnets, which just allows free room

FERRANTI ALTERNATING CURRENT DYNAMOS.

Rope Driven.

OUTPUT.		WEIGHTS AND DIMENSIONS (Approximate).									EXCITER.	
E.H.P. at Dynamo Terminals.	Safe Load in 10 c.p. Lamps (35 Watt).	Speed or Revolutions per Minute.	Weight, including Exciter, in Tons.	Entire Length over all, including Exciter.	Width of Machine opened out, *i.e.*, total width over Extension Plates.	Width of Machine closed.	Height.	Diameter of Pulley on Rope Centres.	Over all Width of Pulley.	No. of Ropes.	Exciting Current in Amps.	E.M.F. of Exciter in Volts.
				ft. in.	ft. in.	ft. in.	ft. in.	ft. in.	ft. in.			
75	1,500	625	5¼	7 0	10 6	4 9	5 0	2 6	1 0	5	17	100
150	3,000	500	7¾	8 0	11 8	5 4	6 0	3 0	1 1	5	30	100
300	6,000	416	18¼	10 7	13 7	6 7	9 3	3 7	2 0	10	150	32
625	12,500	250	35	17 10	23 0	10 0	10 2	5 0	3 8	20	96	100
1,500	30,000	208	75	23 0	29 6	15 0	16 6	8 0	7 8	40	300	60

for the coils to move. The width of the armature coils varies from half an inch to one inch.

In the 150 horse-power machine the armature coils are built of copper strip ·012in. in thickness and half an inch wide. In the 300 horse-power machine the copper strip is ·04in. thick and ·625in. wide. In the 625 horse-power machine, there are 2 strips in parallel, each ·024in. in thickness, and ·625in. wide; and in the 1,500 horse-power machine the strip is ·02in. in width and 1in. wide. In all cases the cross section of the strip is sufficient to give ample current carrying power for the particular size of machine. The edge of the copper strip being exposed to the air assists ventilation, and, furthermore, a series of metal wings, cast on to the bobbin-holders, act as a fan when moving, and draw air in to keep the armature cool.

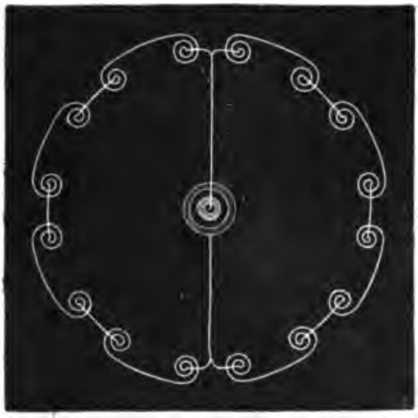


FIG. 132.—Mode of Connection of Bobbins in Ferranti Armature.

The table of the different sizes of Ferranti alternators now made, is given on the previous page.

The number of magnet poles on each side of the frame is respectively 16, 20, 24, 40 and 48 in the five sizes, viz., the 75, 150, 300, 625, and 1,500 horse-power machines.

Besides these rope-driven alternators the same machine is arranged for direct-driving in sizes shown on the next page.

Ferranti Alternating Current Dynamos (for coupling direct to High-speed Engines).

OUTPUT.			WEIGHTS AND DIMENSIONS OF DYNAMO (Approximate).					EXCITER.	
E.H.P. at Dynamo Terminals.	Safe Load in 10 c.p. Lamps (35 Watt).	Speed or Revolutions per Minute.	Weight, including Exciter, in Tons.	Length over all from Coupling over Exciter.	Width of Machine.	Height from Floor Line.	Ground Space required.	Exciting Current in Amperes.	E.M.F. of Exciter in Volts.
				ft. in.	ft. in.	ft. in.	ft. in. ft. in.		
70	1,400	460	5¼	5 0	7 3	5 0	7 3 × 5 10	16	100
160	3,200	400	7¾	5 5	8 0	5 9	8 0 × 7 0	30	100
240	4,800	350	14	6 4	8 8	6 6	8 8 × 8 2	130	32

The excitation of the alternators is effected by means of a small direct-current machine driven from the same shaft in the case of the small sized alternators, but by separately driven independent exciters in the case of the larger machines. The exciting amperes and volts of each size are given in the last two columns.

The lubrication of the machines has been carefully considered. In the smallest size a small oil pump is worked by a belt off the shaft, and forces oil through all the bearings. In the 300, 625, and 1,500 horse-power sizes, an eccentric on the shaft drives a pair of oil pumps, which force oil at considerable pressure into the underside of all the bearings, from which it drains out into a cistern in the framework of the machine, and is pumped back again. The same oil, therefore, goes round and round very often for months together.

The field magnet frame, as above stated, parts along a certain line, and is capable of being separated by a power arrangement, to enable the armature to be reached. In the largest size of alternator as employed at Deptford, this separation is effected by means of a small barring engine.

The usual voltage of these alternators is 2,400. For the cases where the largest sizes are used at pressures above this amount, viz., at 5,000 or 10,000, special arrangements are required to prevent the armature from discharging electrically against the field magnets. These will be described later on.

The current is taken off the machine by rubbing contacts which press against one or two insulated collector rings fixed on the shaft. These collector rings are enclosed in a metal box with glass sides, which is arranged as shown in Fig. 133, so as to be inaccessible.

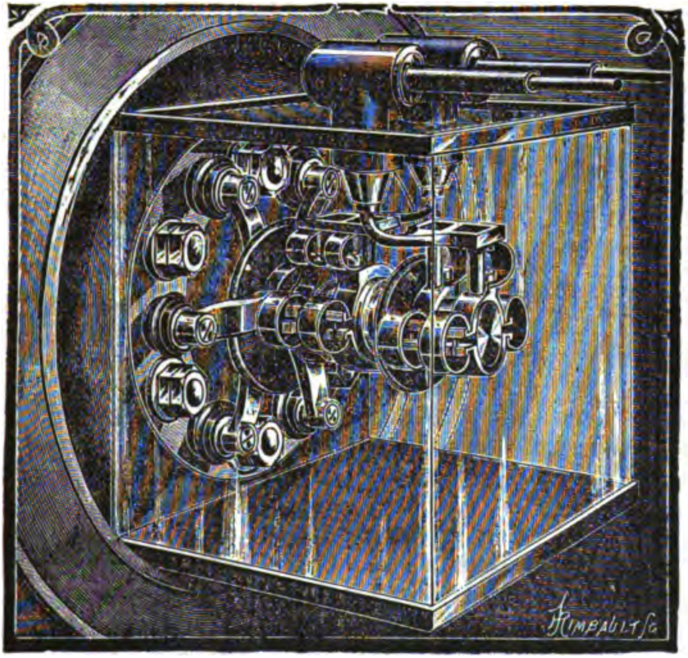


Fig. 133.—Collector Rings of Ferranti Alternator.

§ 35. **Ferranti Transformers.**—The general construction of the Ferranti Transformer has already been described at the end of Chapter I. Great care is taken in the selection of the iron for these transformers, and in the general design, to diminish as far as possible the "drop" due to magnetic leakage, and also to obtain a high efficiency. The standard pressures between which these transformers work is most usually 2,400 to 100 or to 50 volts, but they are also wound during the transformation from 2,000 volts to 100 or 50. They are made in the sizes shown in the table below.

FERRANTI TRANSFORMERS.

Output in electrical horse-power.	Output in watts.	Safe secondary load in 35 watt lamps.	POTENTIAL IN VOLTS.	
			Primary.	Secondary.
1	740	21	2,400 or 2,000	100 or 50
2½	1,865	53	,, ,, ,,	,, ,, ,,
5	3,730	106	,, ,, ,,	,, ,, ,,
10	7,460	213	,, ,, ,,	,, ,, ,,
15	11,190	319	,, ,, ,,	,, ,, ,,
20	14,920	426	,, ,, ,,	,, ,, ,,
50	37,300	1,065	,, ,, ,,	,, ,, ,,
100	74,600	2,131	,, ,, ,,	,, ,, ,,
150	111,900	3,197	10,000 or 5,000	2,400 or 100

The 150 H.P. transformer is especially designed as a sub-station instrument for reducing pressure from 10,000 or 5,000 to 2,400 or 2,000 volts. A general view of the 150 H.P. transformer, transforming from 9,600 to 2,400 volts, or in a 4 to 1 ratio, is shown in Fig. 134. This transformer consists of three coils—viz. of one high-pressure coil, which is sandwiched in between two low-pressure coils. Each of these coils is composed of copper strip separated by a strip of vulcanised fibre, like the armature coils, and wound over with shellaced cloth and vulcanised fibre. In forming these coils, a number of separate flat coils are built up one over the other, and connected together in series, insulating material being placed between every elementary coil. The high-pressure and low-pressure coils are separated from one another by sheets of ebonite, with a considerable air space between. The iron cores are exceedingly massive, and formed, as described in Chapter I., of flat bands bent over in opposite directions to form closed magnetic circuits; the various layers of iron bands are separated from one another by an air space of ·5 inch, to provide for ventilation, or, in cases

where the transformer is placed in oil, to allow a free circulation to the oil.

It is advantageous to immerse these high-tension transformers under the surface of an insulating fluid, diminishing thereby the liability to electrical discharge between the high-pressure coil and the iron frame, or the low-pressure coil which exists in virtue of the powerful electrostatic field in the neighbourhood of the high potential end of the high-pressure coil.

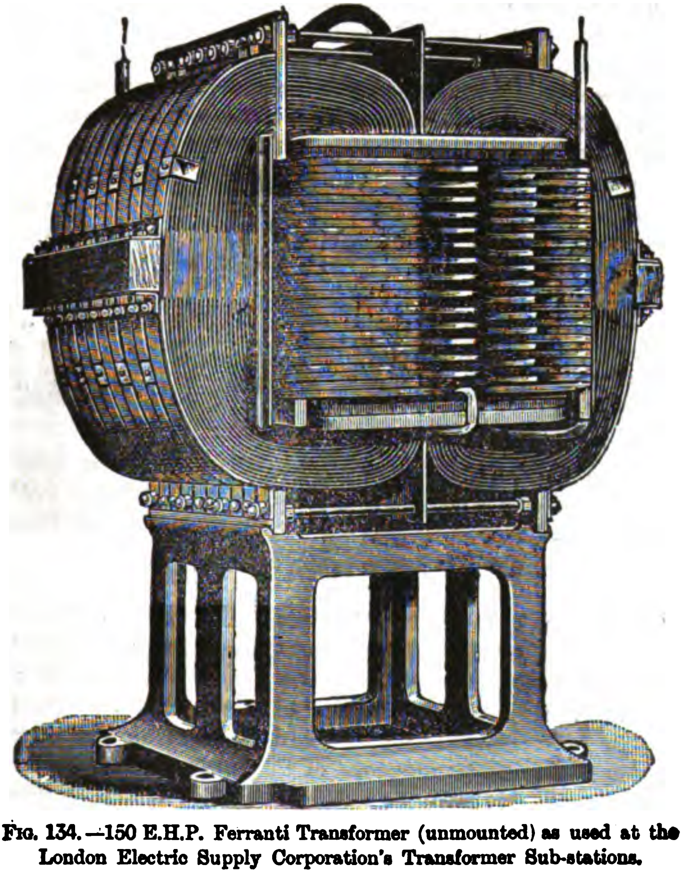


FIG. 134.—150 E.H.P. Ferranti Transformer (unmounted) as used at the London Electric Supply Corporation's Transformer Sub-stations.

§ 36. **High-Tension Fuses and Switches.**—In connection with the primary circuits of all transformers high-tension fuses are used on both poles. These consist of a stoneware box, as shown in Fig. 135, having a sliding lid. In the groove in the box lies a fuse wire composed of one or more strands of tinned copper wire. This fuse wire is soldered to two brass plugs, which drop into sockets at the extremity of the fuse box, into which the ends of the cables are made fast. The length of fuse wire in the house service box is about 12in., and for the station fuse box about 24in. This great length of break is found necessary to prevent arcing when the fuse wire melts. The fuse boxes are mounted on india-rubber pads to insulate them from the earth. The high-tension switches consist of a double-pole switch enclosed in a box with a glass front, and which is moved from "on" to "off" by means of an ebonite handle outside the box.

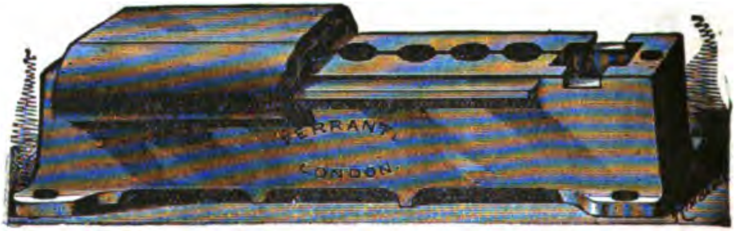


Fig. 135.—High-tension Fuse Box.

§ 37. **Ferranti Concentric Mains.**—Mr. Ferranti designed for the London Electric Supply Corporation a form of concentric main, intended for extra high-pressure service. This main is made in lengths of 20ft., and is jointed together by electrical and mechanical joints of an ingenious character. In the manufacture of this main, brazed copper tubes are taken, having equal cross sectional area, either ⅛in., ¼in., or ½in. section, calculated respectively to carry 125, 250, or 500 amperes. In the ¼in. section main, the copper tubes have the following dimensions. The inner conductor, or inner member, is a copper tube (*see* Fig. 136) of which the inside diameter of cross section will be called D_1, and radius R_1, and the outside diameter D_2, and radius R_2. The outer conduct, or member, is a copper tube of which the inside diameter will be called D_3, and radius R_3, and its outside diameter D_4, and radius R_4. The insulation between the inner and outer members consists of brown paper saturated with black wax. The values of the diameters and radii of cross section of these tubes are as follows:—

$D_1 = \frac{9}{16}$ of an inch = ·5625 in.
$D_2 = \frac{13}{16}$ „ „ = ·8125 „
$D_3 = 1\frac{27}{32}$ „ „ = 1·8437 „
$D_4 = 1\frac{15}{16}$ „ „ = 1·9375 „

Hence we have—

$R_1 = \cdot 281$ in. $\qquad R_1^2 = \cdot 0789$
$R_2 = \cdot 406$ „ $\qquad R_2^2 = \cdot 1648$
$R_3 = \cdot 922$ „ $\qquad R_3^2 = \cdot 8500$
$R_4 = \cdot 969$ „ $\qquad R_4^2 = \cdot 9389$
$R_2^2 - R_1^2 = \cdot 0859$,, $\qquad R_4^2 - R_3^2 = \cdot 0889$

Hence the area of cross section of the inner member is $\pi (R_2^2 - R_1^2) = \cdot 2689$ sq. in., and that of the outer member is equal to $\pi (R_4^2 - R_3^2) = \cdot 2793$ sq. in., or approximately a quarter of a square inch. The copper resistance of the quarter-inch section main is ·324 legal ohm per mile run (including lead and return) when laid. The electrostatic capacity between inner and outer members is ·367 microfarad per mile run, and the capacity between the outer member and the iron casing about ten times as much. The inductance is 286 microhenrys per mile, and the dielectric resistance between inner and outer copper about 700 megohms per mile. The process of manufacture of these mains is as follows:—

The tubes having been strained and cleaned, the interior tube is wrapped with layers of brown paper, which have been heated, and passed through a black mineral wax. This waxed paper is rolled tightly round the copper tube, whilst the wax is warm, in a special machine; several sheets are employed, one over the other, building up an insulating covering which, in the case of the $\frac{1}{4}$in. section main, has a thickness of $\frac{1}{2}$in. The tube so covered is then slipped in the outer copper tube, and the outer copper tube is drawn down through a die, over the inner copper tube, compressing the outer tube and the insulation tightly together. The outer copper tube is then insulated again with waxed paper rolled up over it to a thickness of $\frac{1}{8}$in., and this insulated pair of tubes is then slipped into an iron protecting tube, which nearly fits it, and molten wax is forced in, to fill up the interspace (*see* Fig. 137). The tubes so prepared, in lengths of 20ft., are then put into a lathe of peculiar construction, and the ends turned down in such a manner that one end is tapered off into a cone, as shown in Fig. 138. The insulating material being tapered down from the end of the outside copper to the end of the inside copper which projects some way beyond the outer tube. The other end of the main is turned down into a recessed or hollow cone, as shown in Fig. 138, the two cones being cut to precisely the same angle, so that the outside cone at the end of one main will fit into the recessed cone at the end of another one. The connection between the two inside tubes is made by forcing in a copper rod *a* (*see* Fig. 139), which is prevented from going in more than a certain length by a little shoulder on the inner copper tube.

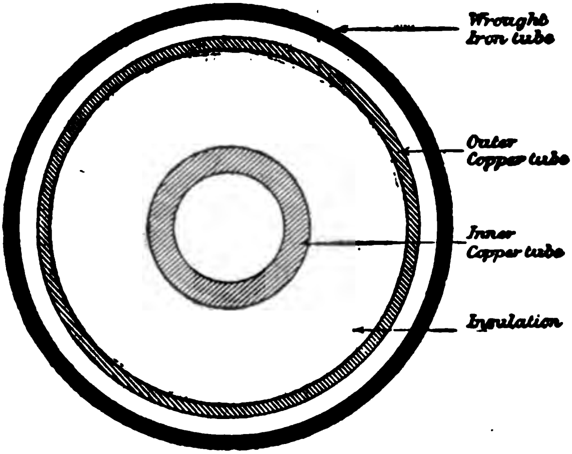


FIG. 136.—Full-sized Sectional Drawing of Ferranti Trunk Main. (¼in Section.)

In laying these mains, the process of making the joint is as follows:—

The 20-feet lengths of main are laid down underground in wooden boxes, afterwards to be filled in with pitch, and the mains are separated by means of wooden bearers. The lengths of main having been laid down in the proper direction, a copper

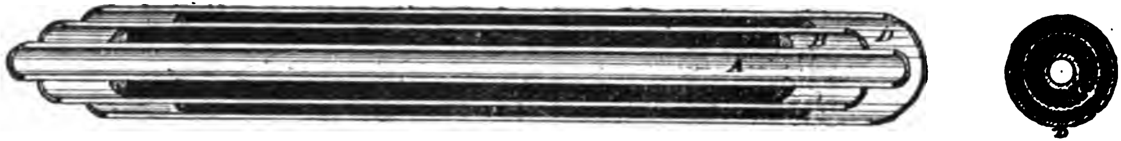


FIG. 137.—Ferranti Main.

A, Inner copper conducting tube. B, Outer copper conducting tube. D, Iron protecting tube. (Insulation shaded black.)

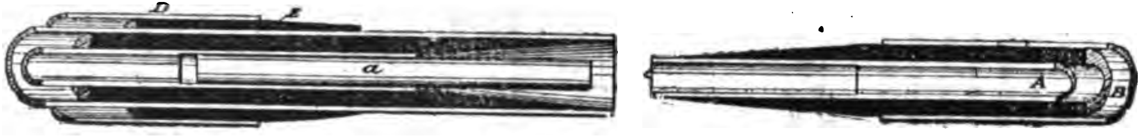


FIG. 138.—Ferranti Main prepared for Jointing.

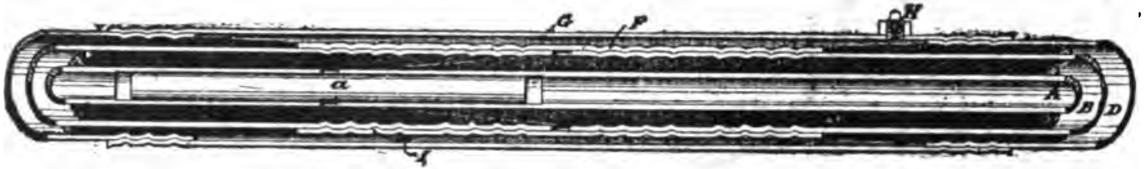


FIG. 139.—Ferranti Main Jointed.

A B, D, as in Fig. 1. *a*, Copper rod. G, Iron sleeve. F, Copper sleeve. H, Screwhole. I, Interspace filled with melted wax.

and an iron sleeve are slipped on over one end of the main. The copper rod is then pushed into the open end of the inner tube, and the two inter-fitting cones of two lengths of the main are forced together by an hydraulic press; the copper rod is rammed half into one inner tube, and half into the other, and forms a good electrical connection between the two inner copper tubes. The copper sleeve is then drawn over so as to connect together the two outer copper conductors, and is corrugated on to them by means of a peculiar tool, which compresses together the outer copper member of each 20-foot length and the copper tubular sleeve which connects them together. This tubular sleeve is represented by F in Fig. 139. In the same way the iron sleeve G is then drawn over and corrugated on, connecting together the iron tubes of two adjacent 20-foot lengths, and the interspace I between the iron outer tubular sleeve and the inner copper sleeve is filled in with melted wax, forced in through a screw hole H, which is afterwards closed. In this way a joint is made in which the insulation between the outer and inner copper tubes is approximately continuous, because the waxed paper cones weld together under the pressure in such a manner that they require very considerable force to pull them apart. In order to allow for expansion, bends are placed at intervals with a slight double curvature of an S shape. The wood troughing in which the mains are laid is then filled up with pitch and a wooden cover is laid over it. At intervals in the main street, test boxes are inserted so that certain lengths of the main can be isolated for the testing. This street box is shown in elevation in Fig. 140. The ends of the cables are brought into the box at opposite

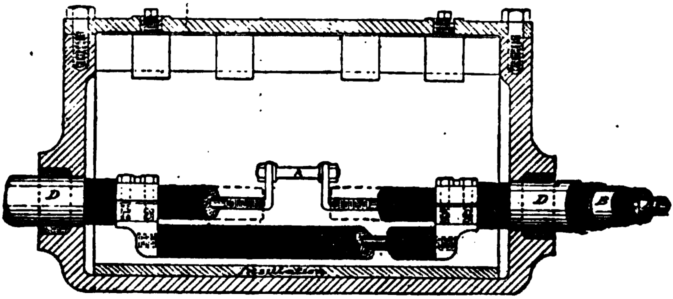


FIG. 140.—Sectional elevation of Street Box.

ends, through stuffing boxes, and the inner copper members are approached to within a short distance. The inner copper members are then connected together by means of a crank-shaped copper connection, so made that by slacking the nuts the crank pin can be withdrawn, and the mains disconnected. The connection between the outer conductors is made by a copper clamp, which is wrapped over with waxed paper to insulate it from the box. The cover of the box is then bolted on, the box edges and cover being tooled to true surfaces. The box is finally pumped full of heavy resin oil. A junction is thus effected, capable of easy disconnection, and yet of withstanding 10,000 volts or more, and which is always able to be uncoupled very quickly for the purposes of isolating and testing certain lengths of main. In cases where the junction has to be effected at right angles a T-joint box is employed of a very similar description. The box parts along the middle line, and the ends of the mains to be connected are brought in through three stuffing boxes; a junction is effected between the inner members by a screw bolt which screws through the inner copper member of the main, and into the end of the inner copper member of the offset. Waxed paper insulation is then wrapped round this part, and the connection between the three outer copper members is made by a copper fork, clamped on as is shown in Fig. 141. When the joint is made the box is pumped full of resin oil.

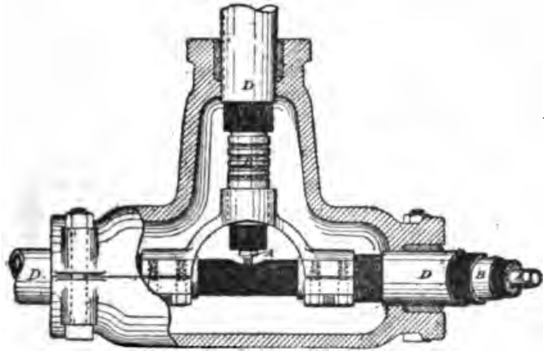


FIG. 141.—Ferranti Main. T Joint.

§ 38. The London Electric Supply Corporation's Deptford Station.—The Deptford Station of the London Electric Supply Corporation was designed by Mr. Ferranti with the object of supplying a large area of the Metropolis with alternating electric current from a station situated considerably outside the limits of the area to be served. A site was selected by the Corporation, on the banks of the Thames, not very far distant from Greenwich Hospital. On this was erected station buildings, of which an outline plan is shown in Fig. 142. The building is a brick and stone structure, about 210 feet in length and 195 in breadth. The engine and dynamo room is divided into two bays, separated by a row of cast-iron columns. A longitudinal girder is carried down both sides of each bay on the tops of these columns as well as on the wall buttresses, and supports the two large overhead travelling cranes, each capable of lifting 50 tons. The traversing and motion gear of these cranes is operated by ropes, worked by auxiliary engines on the floor. The roof is an iron and glass structure, the distance from floor to roof being 100 feet. The boiler-room is designed to contain two tiers of Babcock and Wilcox water-tube boilers. Of these the lower tier of twenty-four boilers are already in place. At each end of the boiler-room rises a smoke stack, the feature of which is that it is divided into four separate shafts by partitions, and each batch of six boilers sends its furnace gases into one quarter of the chimney. The height of the shafts is 150 feet. The feed-water supply is taken from a large tank capable of holding 800,000 gallons of water. The feed pumps are in duplicate, and are placed in the engine-room.

The boilers are each nominally of 500 horse-power, and are arranged in four batches of six each. Beneath the boilers is placed a forced draught engine to facilitate steam generation during sudden loads. The coal for these furnaces is landed at the wharf from the river, and then transferred by means of a travelling locomotive crane from the river side direct to the ashpits by means of a line of railway which runs right down the centre of the boiler and engine house. A noteworthy feature of the steam supply system is the "multiple" steam pipe, employed to obviate the risks incurred by the use of single steam piping of large diameter. In consequence of a serious accident by the explosion of a bend in a copper steam pipe at

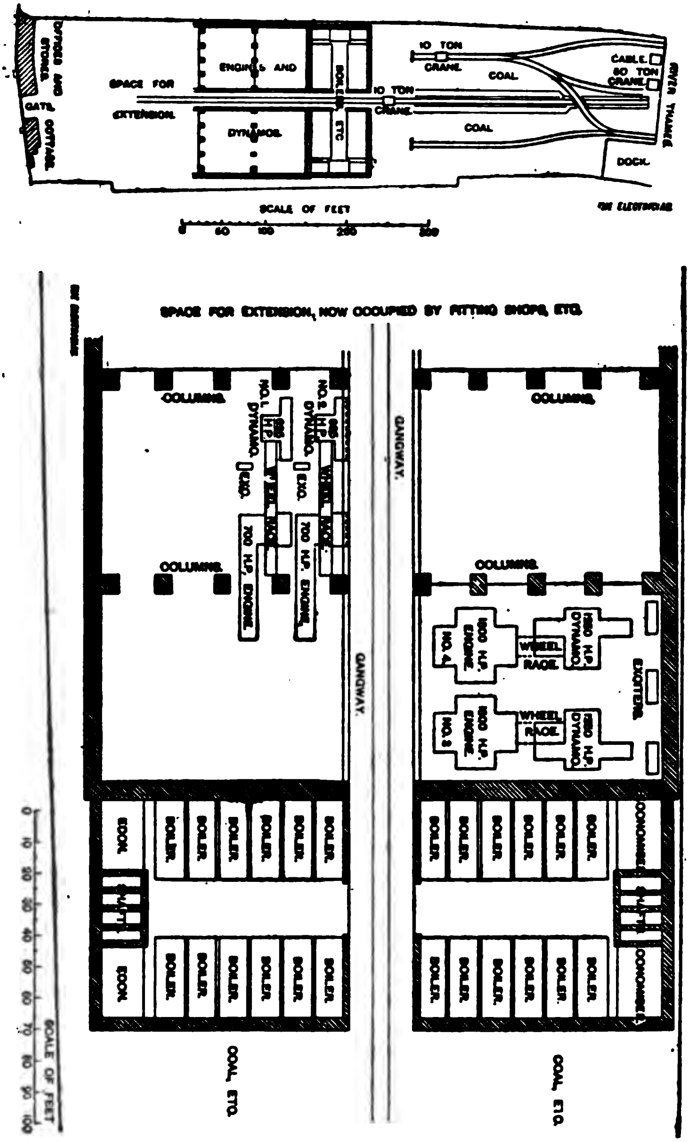


FIG. 142.—Plan of the Deptford Electric Lighting Station.

Deptford, Mr. Ferranti invented a system of steam piping which is in a high degree free from the usual risks. It consists in forming a large pipe of a bunch of smaller solid drawn copper tubes.

It is possible that this idea of bunching pipes together may not be altogether new, but the great difficulty would naturally be, in an ordinary way, how to fix the pipes into suitable flanges. Brazing would probably have to play an important part, and the risk of rupture or explosion would be multiplied by exactly the number of pipes used in the construction of the bunch.

Mr. Ferranti, therefore, at once appears to have discarded any idea of brazing his pipes into the flanges, and adopted, after one or two experiments, a new system. All pipes are expanded into the flanges, and single pipes are connected with as few flanges as possible, and this possible is reduced to a minimum by the adoption of a joint consisting of a sleeve arrangement. Two lengths of solid drawn copper pipe, of any suitable diameter, have a certain number of rings corrugated on their surface close to the end, the corrugations being to a pitch which has been determined upon, and to a depth which is definite. The two ends of the pipes thus corrugated are then placed "end on" to each other, and a sleeve of copper, a sliding fit over the pipes and sufficiently long to well cover all the corrugated rings, is drawn over the joint (*see* Fig. 143). This sleeve is then corrugated down into the grooves in the

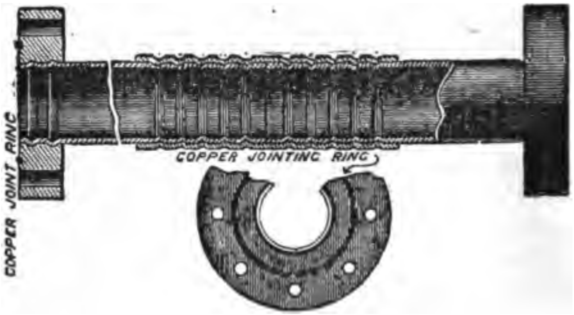


Fig. 143.—Sleeve Joint of Ferranti Steam Pipe.

inside pipes, and without any mandril being used a perfectly steam-tight connection is made. A test to which this style of joint was subjected was as follows:—The two tubes were each 4in external diameter, and were of $\frac{1}{8}$in. in thickness; five corrugations $\frac{3}{32}$in. deep were made in each; these rings having a pitch of 1in. The corrugated ends of these pipes were then inserted into an outer copper sleeve $\frac{1}{8}$in. thick and 12in. long, which was a sliding fit on the pipes. The sleeve was then corrugated down into the corrugations already existing in the inner tubes, and the ends of the pipes were next fitted into their connecting flanges and fixed therein. Such a joint was subjected to hydraulic pressure up to 2,000lbs. on the square inch, without causing the joint to break at the sleeve. The connecting flanges are about 2in. thick, and have two grooves turned in them to a standard gauge, the grooves being about $\frac{3}{32}$in. deep, and $\frac{3}{8}$in. broad. The flanges are a tight sliding fit over the ends of the tubes, and, having been slipped to their place, a special expanding tool is introduced into the tubes, and the tube is rolled or corrugated into the grooves in the flanges, and makes a very tight firm joint. If any of the end of the tube overhangs the flange, it is next trimmed up, and the thing is finished; the whole operation of affixing a flange occupying about one-third the time taken by a first-class coppersmith in brazing an ordinary old-fashioned flange on to a tube of similar dimensions. In making main steam-pipe seven smaller solid drawn copper tubes are fixed into common flanges (*see* Fig. 144). The seven pipes, having been fitted into the holes for them in the flange, are corrugated, and finally fixed exactly in the same manner as is the single pipe in the small flange described above; and when a length of pipe is finished with its pair of flanges, it is subjected to what is considered a test pressure sufficient to prove the workmanship of the corrugating. The pipes and bends being all of heavy and solid drawn copper may generally be taken, considering their small diameter, to be beyond reproach, so far as safely withstanding any working pressure, however high, is concerned (*see* Fig. 145). The peculiar box flange, and which is known as a "special" A flange, is used where the end of a line of multiple steam pipes is to be joined to the steam drum of the boilers, to a stop valve, or to the valve casing of the engines, and the pipes are fixed into it in the same manner as into the ordinary standard multiple flange.

In its uncovered state the Ferranti pipe has this disadvantage, that it has much in common with a surface condenser, but it is easily covered, and then there is no practical disadvantage due to the increased area of surface, against which the steam must brush. As a matter of fact, there is at Deptford one multiple pipe which delivers steam to a pair of 700 horse-power engines 130 feet away from the boilers with a loss of not more than five per cent. of pressure. If there is,

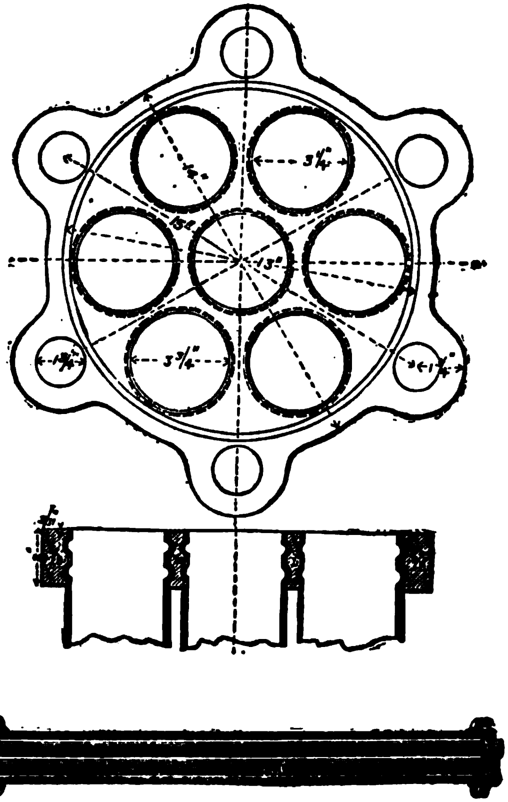


Fig. 144.—Ferranti Multiple Steam Pipe and Flange.

therefore, nothing to be found in this objection which theorists might raise to the multiple pipe, then all we can say is that the practical advantages are many and great; and a few of these advantages appear to us to be :—

1. An enormously reduced probability of explosion, due to the very great increase in strength of the multiple over the single pipe, for the same area.

2. In the event of explosion, the absence of, or much minimised danger of damage to life or property, owing to the fact of the small flow of steam, by the failure of one small pipe, for we cannot regard the failure of more than one pipe as being at all probable.

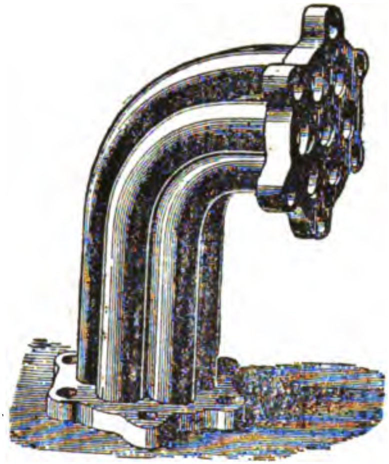


FIG. 145.—Bend of Ferranti Steam Pipe.

3. The ease and certainty of obtaining tubes of a uniform thickness throughout, the increase in strength of solid-drawn pipes due to the drawing operations, and the obtaining of copper of a definite standard condition.

4. The elimination of most of the objections to brazed pipes, as there will be no thinning of the metal at any point, no weakening due to over-heating, and no draining of molten spelter through the joint. Beyond this the serious danger of producing incipient flaws when planishing or scarfing the edges of the copper plate is entirely obviated.

5. The great increase in the flexibility of the bends, &c., and the consequent ease in making due and sufficient allowance for expansion and contraction.

All the steam piping at Deptford is erected on this system, and has reduced the usual risks of large steam pipes and bends to a minimum quantity. The steam-generating plant delivers steam to four engines at present erected (1891) in the engine-room, viz., two of 1,500 horse-power and two of 700 horse-power. Our illustration (Fig. 146) shows a view of one of the 1,500 horse-power engines and dynamos. These engines are all compound Corliss engines, built by Hicks, Hargreaves, and Co., of Bolton. The two smaller engines are horizontal engines with tandem cylinders. The flywheel, weighing 35 tons, is 24 feet in diameter, and drives its associated dynamo by 17 ropes running in grooves in the flywheel edge. The larger engines (1,500 horse-power) are vertical engines, having a flywheel 22 feet in diameter, and weighing 60 tons, slung on swivel bearings between the high-pressure and low-pressure cylinders. The stroke of these engines is four feet. The low-pressure cylinder is 56 inches in diameter, and the high-pressure 28 inches. The driving power is transmitted to the dynamo by 40 five-inch ropes, running in grooves in the periphery of the flywheel. The dynamos driven by these engines are of the form described in a previous section. The two 700 horse-power engines drive each a 625 horse-power alternating-current dynamo, which generates current at 2,400 volts, and this pressure is raised to 10,000 volts by means of step-up transformers. The fields are excited by means of a Siemens direct-current dynamo, driven by rope gearing from the dynamo shaft. These exciters furnish current at 100 volts up to 98 or 100 amperes, which is the maximum exciting current required. The exciting current required is varied by a rheostat which throws in resistance into the exciter circuit. This rheostat is manipulated from the main switchboard.

The alternators have forty field poles on each side, and the field coils are connected in eight sets of ten each, the eight sets being joined in parallel. The speed of the armature is 250 revolutions per minute, and it consists of forty bobbins. The width of the armature strip is five-eighths of an inch. Each of

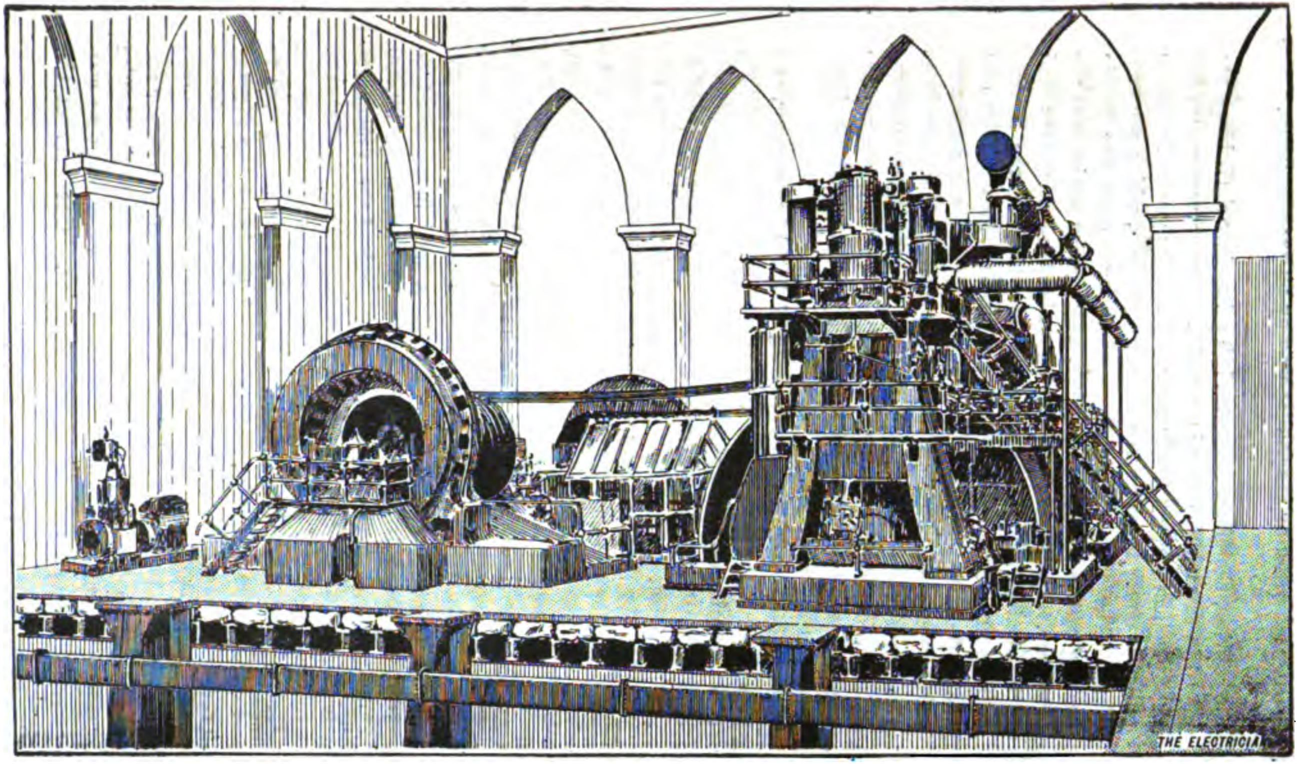


FIG. 146.—1,500 H.P. Engines and 1,250 H.P. Dynamos in the Deptford Electric Lighting Station.

the bobbins, therefore, generates 120 volts, since the bobbins are joined in two equal series in parallel. The current comes out at two collector rings fixed on the shaft. The grooved dynamo pulley is slung between two massive bearings, which are self-oiling. The part of the shaft which overhangs the inside bearing carries the gun-metal hub, which forms the basis of the armature. The bobbins are carried on bobbin-holders insulated with porcelain shank insulators, and the bolts of the bobbin-holders are cemented with sulphur cement into the hub as before described. These machines can furnish a maximum current each of 200 amperes at 2,400 volts. The current at this pressure is passed through four to one step-up transformers, and raised to 10,000 volts. These machines are used at present (1891) for the daylight load, and for light loads during the night.

The two larger dynamos are each of 1,250 horse-power, and generate current directly at 10,000 volts. In these machines, of which an enormous grooved pulley (*see* Fig. 127) is the most striking feature, the armature consists of 48 bobbins, and is about 13 feet in diameter over all, and the bobbins are one inch in width. The field magnets have 48 field poles on each side, and the two halves of the field magnets can be slid on the bed plate, so as to separate the parts and expose the armature. This movement is effected by a small auxiliary engine. The field-pole coils consist of copper strip insulated with vulcanized fibre put between the layers. The exciting current is about 400 amperes at 50 volts. These armatures are driven at 208 revolutions a minute, and can furnish a maximum current of 100 amperes at 10,000 volts, or sufficient to maintain 30,000 30 watt lamps. The height over all of each of these machines is 14 feet 6 inches. In order to prevent lateral discharge of the armature, the faces of the field poles are covered with a pair caps of ebonite or woodite. These caps are each tested to 15,000 or 20,000 volts, and then held firmly on the faces of the field poles. But for this arrangement, the high tension would cause the armature to discharge against the fields. The current is led out of one side of the armature by a copper rod insulated in the interior of the armature shaft by an ebonite tube. The other end of the armature is in conducting connection with the frame of the machine. One pole of the machine is thus always "to earth" and the other pole or "live pole" is insulated and sends current through the collector rings to the mains. The collector rings are on the end of the shaft opposite to the pulley, and are enclosed in a glass panelled box for safety.

Special attention has been paid to the lubrication of the machines. At one end of the shaft is a double set of oil-pumping gear, which forces oil through the bearings and circulates it round through a filter back into the tank. The main bearings are cast hollow and can have water forced through them if required. The exciting current for these two 1,250 horse-power dynamos is furnished from three slow-speed Kapp dynamos, direct driven by compound Allen engines at 200 revolutions per minute. These exciters are placed along the wall in the immediate neighbourhood of the large dynamos. The switchboard arrangements are as follows:—The main current from the two large dynamos and the main current from the two smaller ones, after being raised to 10,000 volts by the step-up converters, is brought to a switchboard, placed between the two large dynamos. Underneath this switchboard are the resistances for regulating the exciting current for all four dynamos. These resistances are worked by long ebonite rods and shifting contacts, from the insulated platform of the switch. There are four main long-break switches which close the circuit of these dynamos on to an omnibus bar. The pressure on this omnibus bar is measured by 100 to 1 step-down transformer, called pilot transformers, attached on the low-pressure side to Cardew voltmeters. Each machine can be synchronised with respect to the omnibus bar by its own separate synchronising transformer. From the omnibus bar proceed four trunk mains of the Ferranti tubular form. These mains run to the four distributing stations in London, viz., Grosvenor, Trafalgar, Blackfriars, and Pimlico stations. The approximate length of each main is six miles.

The dynamos contribute their current in parallel on to the omnibus main, and the current is then transmitted at 10,000 volts to the sub-stations. At these localities it is reduced to 2,400 volts in pressure by means of sets of 150 horse-power reducing transformers, and the reduced current is supplied to transformers placed in the customers' premises, which still further reduce the pressure to 100 volts.

The system of distribution adopted is one in which the outer conductors of the concentric Ferranti trunk mains and the outer conductors of the concentric Siemens or Fowler-Waring intermediate cables are kept "to earth" at the generating ends.

Thus at Deptford one pole of the omnibus bar is "to earth" and the outer conductors of the four trunk mains are therefore also to earth. At the distributing stations the outer surfaces of the intermediate cables which carry the current at 2,400 volts are "to earth." The iron cores and frames of sub-station transformers are also "to earth."

The object of this "earthing system" is to prevent any sudden alteration of pressure on the inner or live side of the main. If a dynamo has both poles insulated, then assuming it to be giving a mean potential difference of 10,000 volts, each pole is alternately 5,000 volts above and 5,000 volts below the earth in potential. If, by any means, one pole of the dynamo is put to earth, the potential change of the other pole will be altered, and will change from 10,000 volts above to 10,000 volts below the earth. Sudden variations of pressure might thus take place over great ranges due to accidental earthing of one side. This is avoided by having one side permanently earthed. Further reference will be made to this matter in the next chapter.

Both on the switchboard at Deptford and at the distributing station there is a complete system of high-tension fuses. Fine tinned copper wire, about No. 40 gauge, is cut into three-foot lengths, and bunches of this wire, according to the current to be carried, is fixed centrally in toughened glass or stoneware tubes by metal stoppers at the end of the tube. These stranded fuse wires are then inserted in the circuit by pushing the tube into a position when it is held at top and bottom by spring-pressure pieces. In inserting or removing a high-tension fuse in a 10,000 volt circuit a sort of ebonite sugar tongs are used to hold the tube. The sub-station transformers are protected both on the 10,000 volt and on the 2,400 volt sides by similar appropriate fuses, and the circuits opened by long break switches placed in series with the fuses.

In the sub-stations are placed sets of the 150 horse-power transformers, which can be connected as desired on the high-tension side to one or other of the trunk mains which enter the station. On the other side they can be connected as necessary to the intermediate mains. Furthermore, the four transformer stations are inter-connected, so that one can help the other. In these transformer stations measuring instruments show the current and pressure on each side of the transformers. The sub-stations themselves are fire-proof chambers, having channels in the floor to receive the incoming and outgoing cables. The necessary switch gear is erected against the walls and in the centre of the room.

This switch gear may be more generally described as consisting of a series of slate slabs placed vertically, which form a set of spaces, in each of which is placed one long break switch and the corresponding high-tension fuse. The switches are worked by long handles, and make two sharp breaks of about 12 inches each in the circuit. The transformers are installed along the sides of the room, and the act of pushing the transformer into its place makes the necessary contacts on the earth side of the outgoing or low pressure (2,400 volts) cable. The circuit is then completed by inserting the fuse tube and closing the switch. The high pressure connections to the 10,000 volt cables are made also through fuse tubes and special long break switches, which break the circuit in four places at a high speed.

§ 39. **Havre Central Station.**—Mr. Ferranti has also supplied the machinery for Havre electric lighting, as carried out by the Société de l'Energie Électrique, which has obtained a forty years' concession, during the first fourteen of which they were given exclusive rights. The central station is near the railway station, and in close proximity to coal yards and to the sea, whence it is proposed to draw the water necessary for condensing purposes. The plant at present comprises four Berendorff boilers, working at 114lbs. pressure; two single-cylinder Corliss engines, taking steam at 86lbs. pressure, and capable of developing 350 horse-power or 450 horse-power at one-ninth and four-tenths cut-off respectively; two 224 kilowatt (2,400 volts) Ferranti alternators, excited by small six-pole

Sautter-Lemonnier machines mounted on the same bed-plate. The dynamos are driven direct through rope gearing (10 ropes 1·4in. diameter). Each engine is fitted with a fly-wheel 22ft. in diameter, and weighing 15 tons. Special arrangements are made for running non-condensing in times of neap tides, and when otherwise necessary. Great attention has been paid to securing efficient lubrication. A small pump fitted to each dynamo takes the lubricant from the large reservoir in the pedestal, which holds some 1,800lbs. of oil and forces it into the bearings at a considerable pressure.

§ 40. **Ferranti Stations in France and elsewhere.**—Many electric stations in France are employing Ferranti dynamos and distributing alternating currents. In Paris, in the *Halles Centrales*, there are three Ferranti 150 horse-power alternators, driven by Lecoutreux and Garnier horizontal Corliss condensing engines by cotton-rope gear. The lighting comprises 120 arcs and 3,000 incandescents. At Nancy there is a similar plant of alternators, driven by two Armington and Sims non-condensing engines and one Corliss engine, and the lighting undertaken is 4,600 16 candle-power incandescents. At Melun also three 150 horse-power Ferranti machines give current for 4,500 incandescent lamps, the dynamos being driven by compound condensing Corliss engines. At Troyes, Sens, Rethel, Nîmes, Dijon, St. Cere, Cannes, and Auxerre there are Ferranti plants at work doing incandescent lighting.

In South America, at La Plata, Rosario, and Buenos Ayres, also Ferranti alternators are employed for public and private lighting.

Mr. Ferranti prefers generally to adopt a Corliss engine and to drive by cotton ropes, but where engine-room space is valuable direct driving by Willans or other high-speed engines can be undertaken.

§ 41. **Other Transformer Systems.**—The descriptions given in the above sections of this chapter by no means exhaust all the forms of alternators and transformers in actual use. The great firms of Schuckert of Nuremberg, and Siemens of London and Berlin, for example, have complete systems of alternate-current machinery. The appropriate limits of the present chapter would be exceeded if detailed descriptions of all these were given, but reference will be made further on to special forms of transformers designed by them. The descriptions above given provide the reader with information as to a number of typical systems, but the progress of invention is so rapid as almost to defy any attempt to place a complete and final account of all transformer systems on record.

CHAPTER III.

ALTERNATE CURRENT ELECTRIC STATIONS.

§ 1. **The General Design of Alternating Current Stations. Motive Power. Selection of Unit.**—In the general design of a system of electric supply by alternating currents, as at present carried out, many considerations have to guide the engineer in the selection of a suitable site, and in the choice of the motive power and the arrangement of the generating plant. At the present time (1891) the selection of a system of electric supply to be adopted for electric lighting of towns is practically limited to one of two systems. First, the system of direct supply, with or without secondary batteries, on the two, three, or five wire systems; and, secondly, the system of alternating current supply, including the so-called rotary field (Drehstom) systems, on the general lines of one or other of the plans described in the previous chapter.

The system of two-wire direct current low-pressure supply is one that is suitable for small districts in which the lighting is dense, and in which the supply station can be placed approximately in the centre of the district to be lit. Experience shows, however, that the economical limits of such a system are reached when the mean length of the feeders is some 300 or 400 yards. By the three-wire system, as developed by Mr. Edison and Dr. Hopkinson, the system of low-pressure supply can be economically conducted when the mean length of the feeders is from half to three-quarters of a mile. The five-wire system is applicable up to a mean distance of one mile. Beyond this distance, we are practically limited to a system of supply based upon alternating currents and transformers. Assuming, then, that the case to be dealt with is one in which the above facts point to the employment of the alternating current system, the first consideration to which the engineer has to address himself is the selection of a suitable site for the station. It will generally be found that the choice is limited to two or three positions, and that questions of convenience, price of land, access, nuisance, and other circumstances bind down the engineer to the selection of one out of a small choice of possible sites. Assuming, however, that an option exists between one or more positions for such an "eccentric station," then the following considerations should have due weight in determining the exact choice to be made.

In the first place, the selection ought to be governed by the consideration of convenience of access for coal and of freedom from creating nuisance by smoke, steam, or vibration. At the outset, when the supply from such station is small, the amount of coal and other stores to be brought into it, and of ashes, &c., to be removed, will not present formidable difficulties, but as the station grows in magnitude this will prove to be one of the most serious items in the economical management of such a station; hence, wherever a river-side or water-side site can be procured, by which coal can be received and ashes removed by water, a great advantage is secured, even omitting, for the moment, the advantages of condensation of exhaust steam.

As every thousand units of electric energy sold involves a combustion of from 4 to 10 tons of coal according to the system of alternating current supply adopted, it is obvious that convenience for handling coal and discharging ashes is of paramount importance, and that interruptions of this work by any conditions of weather ought to be practically impossible. With this object the engineer will naturally provide, under these circumstances, for convenient access by road; also, if possible, a connection with a railway siding, and will see that, in addition, a storage for coal is provided, to render it feasible to purchase and store two or three months' supply of coal, thus rendering the station independent of strikes or trade complications. Assuming that such water-side site is procurable, the next question is the general design of a station. In this matter the greatest possible mistakes have been made in many existing stations, either in designing them on too small a scale at the beginning, without sufficient provision and arrangements for extension, or else in designing them at first on too large a scale. The object to be aimed at should be to lay down the station on such general lines that it is capable of considerable extension, as required, without in any way interfering with the existing plant or interrupting the current supply, but at the same time not to involve the enterprise in its initial stage in too large a capital outlay in buildings, on which at first no adequate return can be made. In many cases electric lighting stations have been put up in a small and temporary manner, resulting in the necessity for entire rebuilding at great cost and inconvenience when the demand for current passes a certain limit. Accordingly, the best general design, wherever it is possible for such stations, is an arrangement in which the building is gradually extended from one end as required. If space is limited, this building may take the form of a single building of several stories, engines being placed on the ground floor, dynamos on the floor above, and boilers on the second floor, stores and offices on the third floor. If ground space permits, a cheaper building can be constructed, taking the form of two sheds, lying alongside or in line with one another, one forming the boiler house and the other the engine and dynamo room, arrangements being made at one end for stores, offices, fitting-shop, &c. The general design of such a station calls for great forethought in all the arrangements, in order to reduce in every way the amount of labour required. Want of prevision in this matter results very often in the erection of a station in which there is a considerable waste of labour, and this is an important item in proportion as the station grows in magnitude. Assuming that a careful choice has been made as to site, having regard to the considerations above mentioned, the next matter which demands careful forethought is the choice of the size of the unit of power and of the unit of steam generating plant, in other words, the sizes of boilers and the engines. On this question, there is at present considerable diversity of opinion. Some engineers prefer to select a large engine unit, guided apparently by the notion that such a large engine unit is more economical than a number of smaller ones of equal total power. This, however, has by no means been demonstrated to be the case. Apart from any other reasons it is clear that if the current supply to any one section of a district is wholly dependent upon one large engine, it is obvious that another of equal size, or equivalent, must be provided as a reserve, and hence 50 per cent. of the plant is always idle. If the unit selected is a smaller one, then, provided that the alternators can be worked in parallel, it is possible to have a much smaller fraction of the engine and dynamo plant kept idle as a reserve. Moreover, a break-down throws out of use a much smaller proportion of the total power. The same, of course, applies to the boilers. Owing to the general nature of the load diagram of the ordinary electric lighting supply station, the maximum demand for current is very many times greater than the mean demand, and moreover the maximum demand from most supply stations exists only for a very small fraction of the whole 24 hours. The ratio between the total number of units sent out from the station in the 24 hours to the amount which would be sent out if the plant were working at its full capacity for the whole 24 hours is conveniently called the *diurnal load factor* of the station; and the ratio between the units sent out from the station in one year, and the total amount which would be sent out if the machinery worked always at its full power, is called the *annual load factor.* Experience shows that the annual load factor for an electric supply station, sending out currents for lighting purposes alone, is not more, in general, than eight or ten per cent. Accordingly, as is now well known, the great difficulty that the electric engineer has to contend with is the fact that for large periods of the 24 hours the generating plant is very lightly taxed, and under these circumstances, unless it is properly subdivided, the efficiency of generation will be very small.

In the selection of boilers the choice lies either between the boilers of the water-tube type, one of the locomotive forms, a modified marine boiler, or the well-known Lancashire boiler. The general cause of the small average net evaporative duty of boilers in stations having a small load factor is the necessity for lighting and firing up the several boilers for only short periods during the evening, so that there is an immense waste of heat from radiation and conduction as the boilers cool down after having been thrown out of use; such losses are of course increased when there are large masses of brickwork in direct contact with the fuel which have to be heated up. For this reason many engineers give the preference to forms of internal firing boilers, such as the locomotive marine boilers or the Lancashire. The use of the ordinary return-tube marine boilers has been limited, owing to the difficulty experienced in transporting them by rail when of large size. A modified form of marine boiler has been constructed by Davey-Paxman (*see* Fig. 1) for use in electric lighting stations. This boiler

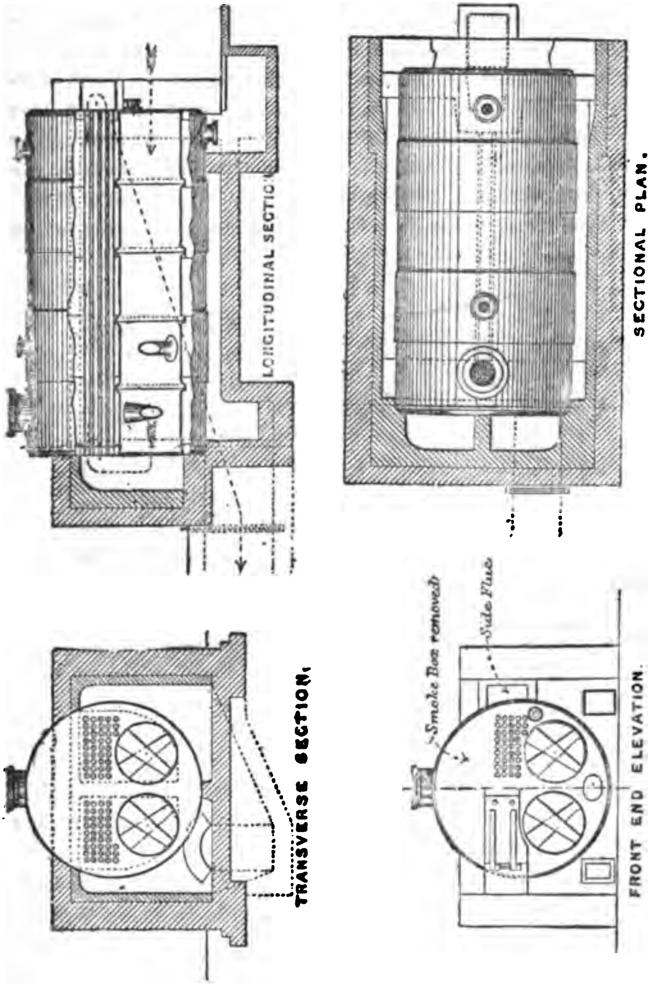


Fig. 1.—Davey-Paxman Dry-back Boiler.

is known as the dry-back boiler; it is not more than 9 feet in diameter, and the furnaces are contained in two cylindrical flues crossed in advance of the firing bridge by a Galloway tube. The products of the combustion pass right through the back, are thrown upwards, and made to return to the front through the tubes by means of the refracted fire-brick dry-back. Mr. Crompton and Mr. Longridge have modified this form of boiler by placing the tubes below the furnaces. The products of the combustion, after passing to the end, are thrown downwards by the fire-brick dry-back, and then passed back to the front of the boiler through tubes placed below the furnaces to the smoke-box or chamber formed beneath the fireman's feet, from whence they pass under the bottom of the boiler on their way to the chimney stack.

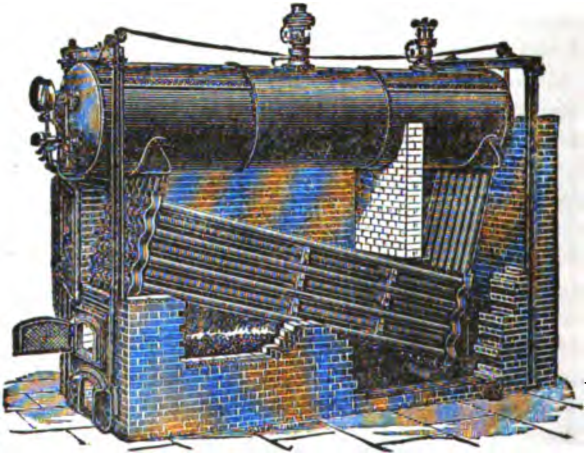


FIG. 2.—Babcock and Wilcox Water-tube Boiler.

Other engineers prefer, where space permits, the employment of the ordinary Lancashire boiler. Formerly difficulty was experienced in making flues of sufficient strength to withstand the high pressure now required; but as this difficulty can, and has been, overcome, this objection is not now valid. On the other hand, the length of this boiler is an insuperable objection to its use in many cases. Amongst well known water-tube boilers used in electric lighting stations, the Babcock and

Wilcox water-tube boiler, a section of which is shown in Fig. 2, is extensively employed. The great recommendations of this boiler are the rapidity with which it can make steam, and the fact that the limit of its evaporative power is only found in the ability of the grate to burn fuel. From its tubular construction it is very free from risk of dangerous explosion, and can easily be transported in sections and erected *in situ*; moreover, it is exceedingly economical as regards space, and from its rectangular form and great vertical height is specially adapted for batches of boilers in central station work where floor space is limited and costly. An objection which has been urged against it is the fact that there are considerable masses of brick-work to be heated up, and which, therefore, absorb and dissipate a sensible amount of heat. On the other hand, for central station purposes, where the demand for steam may, owing to fogs, suddenly become very considerable, it is of the greatest possible advantage to have a boiler which can be suddenly called upon for a considerable delivery of steam, and in which there is great safety and freedom from risk by explosion. Both these qualities are possessed by the Babcock boiler.

Mr. Raworth has suggested an arrangement intended to reduce the enormous waste of fuel in getting up steam in boilers which are used only during the maximum hours of demand. The boilers are erected in groups of three, with flues and condensers so arranged that when the central boiler is being used the products of combustion may be diverted through the furnaces and flues of one or both the other boilers. During the hours of light demand when the middle boiler alone is being used, the exhaust steam from the pumps and supplementary engine is turned into the idle boilers, until the water in them attains a temperature of 212°F., the additional heat required to raise steam being supplied by the products of combustion taken from the central boiler. When the steam in the idle boilers has risen to working pressure, they may, when required, be put into use and fires lighted; the gases from the central boiler being taken direct into the chimney. The method of applying the exhaust steam from the supplementary engines is as follows:—The supplementary exhaust pipe is carried across the whole range of boilers and a branch provided to each boiler, governed by a cock or screw valve. An outlet from the supplementary exhaust pipe is provided into the atmosphere covered by a mushroom valve of considerable size, weighted to 1lb. to the square inch, and provided with an arm by which it can be raised to give free exit. The branch pipe to each boiler is attached to a block on the cover of the shell, and an internal pipe is carried down in continuation of the external pipe to about one foot below the working water level, where it turns at right angles to the vertical pipe, and is furnished with a circulating nozzle. When it is desired to heat up any boilers, the valve between the supplementary exhaust pipe and the boiler is opened, the exhaust valve to the atmosphere is closed, and the exhaust steam from the supplementary engines will be condensed in the boiler. As the water in the boiler increases in temperature the back pressure will increase, but will never exceed the 1lb. to the square inch. In the case of water-tube boilers, it is necessary to attach a distributing box to the discharge orifice of the nozzle, and to take from it pipes leading to each of the tubes in which the natural circulation is downwards. This is necessary to set up the circulation of the whole of the water tubes in the boiler. We are not aware that this plan has been put in practice anywhere, but it is an indication amongst others that the economy of fuel in steam generating is beginning to receive more serious attention than it has done at the hands of electrical engineers.

In the selection of engines the choice of the engineer lies between dynamos driven direct coupled to the engines, and those in which the dynamos are driven by belts or by rope gear, the latter being either the single endless rope-gearing with jockey pulley, or the multiplex rope gearing with the usual groove pulleys and grooved fly wheel. The direct driving has been considerably assisted of late years by the improvements which Mr. Willans has effected in the high-speed compound engine. Wherever space is of importance, direct driving by high-speed engines is almost a necessity. Where space is available many engineers still prefer to drive the dynamos in groups either from the fly-wheel of the engine or from a counter-shaft, owing to the lower engine speeds which are then possible. Whichever method be chosen, the first question to be settled is the selection of the dynamo unit. It is not necessarily an advantage to have these units of the same size. Owing to the small demand for lighting current during the greater portion of the day and night, it is generally best to select one pair of units (one being a reserve on the other), of such a size that one of them will be fairly well loaded during the greater portion of the day, and to select the other dynamo units of such larger size that the output of each machine is from one-sixth to one-tenth part of the full output of the station at its hour of maximum load during the winter.

The very poor economy which some stations exhibit in the matter of coal consumption may be also often attributed to the selection of too large an engine or dynamo unit. It must be borne in mind that compound non-condensing engines are not economical in steam consumption at low loads. It is found that at low loads indicator diagrams taken from high and low pressure cylinder show that the low-pressure cylinder is contributing very little to the total work of the engine, and under some circumstances the diagram of the low-pressure cylinder may even be a negative area, indicating that part of the power of the engine is being used to drive the low-pressure cylinder as a pump. It is, therefore, of great importance to select the engine and dynamo unit of such size that, under any circumstance, the generating plant in actual use is fairly well loaded. The theory that large engines essentially have a greater economy than small ones is not by any means generally true; and on the other hand, owing to the variation in the load, large non-condensing compound engines will often exhibit a relatively very much lower economy at the low loads in weight of steam used per indicated horse-power than smaller and well-designed high-speed high-pressure engines. Engines used for electric light work are under the great disadvantage that they must run at the same speed whether doing much work or little, and hence the only way in which the low station load factor can be neutralised is to give each engine individually as large a load factor as possible.

§ 2. **Condensation.**—It has been shown that the application of condensers to central-station engines enables much higher generating efficiency to be obtained at low loads, that is to say, that condensing plant, although it increases the economy when the steam dynamos are running fully loaded, has greater effect in reducing the loss of efficiency when they are only partly loaded. Mr. Crompton found this to be very noticeable at the Gothenburg Central Station, where there are dynamos rope driven by 200 H.P. vertical triple-expansion condensing engines. During the first year water for condensing purposes was not available, and the engines had to be run at high pressure, exhausting into the atmosphere. Although the consumption of coal was not found to be excessive at the time of highest load, yet such a saving was effected at the time of low loads, when the condensing plant was put into action, that the total fuel consumption for the year was reduced by 60 per cent. This fact has also been brought out by some important experiments

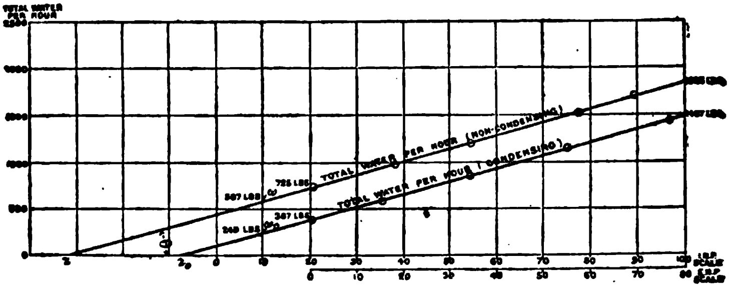


FIG. 3.

made by Mr. Willans, in which he illustrates very forcibly the truth of the above statements.

Mr. Willans has made special experiments with one of his own engines, to test the effect of condensation on the steam consumption of the engine at various loads. These experiments are charted in the above diagram, being reduced for simplicity to the equivalents for a 100 H.P. engine. The water per hour used by the engine is represented by the vertical ordinates in Fig. 3, and the horizontal distances are the indicated horse-powers of the engine. The diagram of the water used per indicated horse-power is a straight line. The line showing the water used when the engine works condensing lies below, and parallel with the line representing the same when the engine is used non-condensing. This diagram shows that the total water used by the engine is proportional to the indicated horse-power *plus* a constant quantity, and that this constant quantity, which is the water used per hour when the engine is running unloaded, is greater for non-condensing than for condensing working. Hence it is clear that condensing increases the efficiency of the engine—that is, decreases the water used per hour relatively more at low loads than at full load. Broadly speaking, if an economy of 18 to 20 per cent. of the feed water could be effected at full load, 40 per cent., or more, might be saved at low loads. These experiments indicate the great value of condensation at low loads, as well as the immense waste incurred in water, and, therefore, in coal by working engines only partly loaded.

In the design of large stations this question of condensing ought, therefore, always to be held in view; and for that reason it is important to locate the station, if possible, in a position in which water for condensation can be procured without pumping the water a considerable distance. For surface condensers the circulating water required will be about twenty times the weight of steam to be condensed, or about at the rate of forty to fifty gallons per hour per indicated horse-power, and hence, for large powers the amount of circulating water required is very considerable. In laying down pipes for the circulating water, or better still, in excavating conduits, allowance must always be made for the full extension ultimately required. In some town stations artesian wells have with advantage been sunk for this purpose; but in any case it is necessary to bear in mind the condensers must be placed in close contiguity to the engines from which they take steam, or else a considerable reduction in the vacuum in the cylinders of the engines will be found. Even if water sufficient for surface or jet condensation cannot be obtained, it is yet worth while, as Mr. Crompton has pointed out, in many cases, to put down air-condensing plant, even if such plant can only be put in of sufficient size to condense the steam at light loads, allowing the exhaust steam at the heavy loads to escape into the atmosphere. Such partial condensation would, in the opinion of many engineers, result in a considerable reduction of the whole coal bill for the year.*

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* *See* Mr. Crompton on the Cost of Generation and Distribution of Electric Energy, *Proc. Inst. Civil Engineers*, Vol. CV., 1891.

§ 3. Utilisation of Water Power.—In many cases water power is available for the purposes of electrical generation, and in these cases the alternating current system presents great advantages in permitting the transmission of considerable quantities of electric energy at high pressures over great distances through comparatively small conductors Considerable improvements have of late years been effected in the means by which such water power can be utilised. Amongst these may be mentioned the Pelton water-wheel, largely used in California and in other places to utilise high falls of water. In this water motor a wheel is provided on its periphery with a series of peculiarly curved buckets (*see* Figs. 4 and 5), and jets

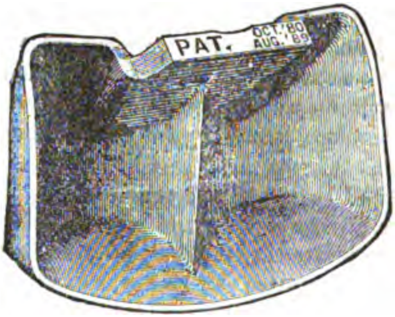
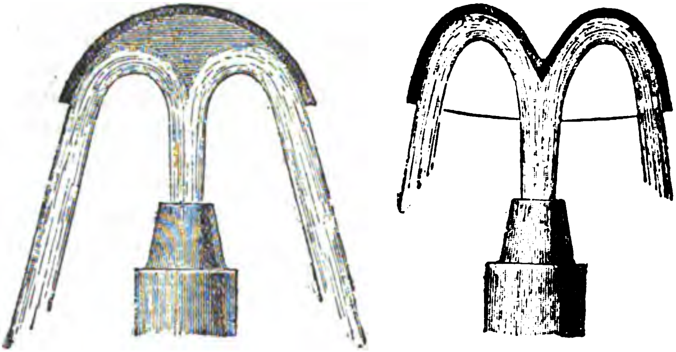


FIG. 4.—Curved Bucket of Pelton Wheel.



A. **B.**

FIG. 5.—**A**, Ordinary Curved Bucket. **B**, Section of Bucket of Pelton Wheel.

of water are thrown into these buckets, setting the wheel in motion. The form of bucket is designed to cause the impinging water to leave the wheel with as little velocity as possible, and hence to give up nearly all its kinetic energy to the wheel. In the practical use of these wheels, water from some source is led to the wheel by hydraulic piping, often from great heights and distances. The best useful effect is found to be obtained when the bucket speed is half the velocity of the water issuing from the jet. Tests have shown that the Pelton wheel has a mechanical efficiency of 87 to 90 per cent. Hence, whenever a natural fall can be obtained, by means of which water can be delivered from one level to a much lower one, this motor enables such energy to be rendered available for conversion into electric energy. A large number of hydraulic electric stations are at work in California, using in some cases falls of water of upwards of 1,600ft. in height, the energy of which is utilised by Pelton wheels. At Aspen, in Colorado, a large electric light and power station is at work, in which some 1,400 H.P. is so utilised by Pelton wheels; amongst the other plant, Westinghouse alternators being employed for incandescent lighting. When hydraulic governors are added to control the wheel-speed, the greatest possible uniformity of driving can be attained, and the Pelton wheel shows itself to be a motor peculiarly adapted for electric lighting purposes.

§ 4. **Water Motor Installation at Tivoli, near Rome.**—One of the finest examples in Europe of water-power utilisation in connection with alternating currents is the new electric station which is being established at Tivoli, near Rome. As is well known, there is at the town of Tivoli a large and valuable supply of water power, and recently a portion of this has been utilised in the establishment of a large alternating current station for 2,000 H.P., intended to supply a portion of the city of Rome with electric light. A part of the Falls of Tivoli is conducted along an aqueduct, at the extremity of which the water falls into a large iron fall-tube, 1·6 of a metre in diameter. This fall-tube is 48 metres in vertical height, and has a capacity for delivering three cubic metres of water per second. At the lower level of the fall-tube the electric station has been erected on the side of the hill, and the fall-tube, terminating near it, branches into three secondary supply tubes, which convey the water into the building. Each of these branches feeds three Pelton water-wheels, two of which are about 300 or 400 H.P. and one smaller. The six larger Pelton wheels are coupled direct to 350 H.P. Ganz alternators of the form described in Chapter II., § 1. The supply of water to each wheel is governed by hydraulic inlet valves which are worked by a sensitive hydraulic relay, the relay being set in operation by a centrifugal governor. By this means the speed is automatically kept constant, independent of the working of the machine. In addition to the six 350 H.P. alternators, there are three other direct current machines used as exciters, which are also driven direct from the smaller Pelton wheels. Each alternator is designed to furnish current at 5,000 volts pressure and 45 amperes. The machines will be driven at a speed of 170 revolutions per minute. Other arrangements for regulating the pressure are arranged as described in Chapter I. The alternating current so generated is to be transmitted to Rome, a distance of 25 kilometres, by means of four stranded copper cables, each being 100 square millimetres in cross section, and capable of carrying 120 amperes. These are to be carried overhead on iron poles placed 35 metres apart, and about 30 feet high, insulated by means of double-shed oil insulators, specially designed for this work by Prof. Mengarini. The lower part of the insulator (*see* Fig. 6) can be lowered to remove or renew

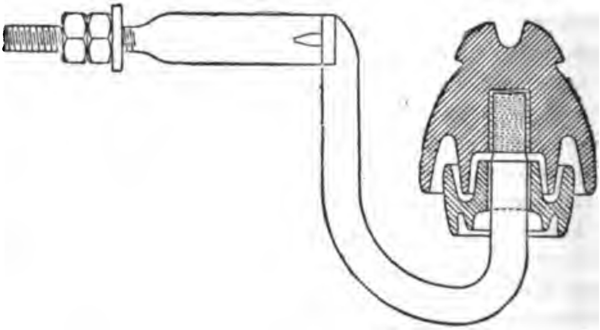


FIG. 6.—Oil Insulator as used for Overhead High-Tension Wire of Rome-Tivoli Installation.

the oil, and when raised into place it keeps the flanges of the upper part wet with oil, and yet renders it impossible or difficult for insects to get round into the interior. A drop of 1,000 volts, or 20 per cent., is to be allowed in these lines. At the far end of these trunk mains the pressure will be reduced by step-down transformers to 2,000 volts, and distributed underground by Siemens cables to secondary centres, at which it will be again reduced to 100 volts. The six machines are all capable of being worked together in parallel, the maximum number of five being used together, and one machine being always in reserve. Two of the exciters are sufficient to supply exciting current to the whole of the dynamos, the third being a reserve.

§ 5. **Arrangement of Alternators.**—Two systems of arrangement of dynamos are in general use in alternating current stations, and have been illustrated in the descriptions in Chapter II.

In the one case, each dynamo supplies current to a number of separate supply lines or trunk mains, on each of which are placed a number of transformers in different premises. Each of these dynamos is independent of the others, and a switchboard is employed by means of which the supply lines can be grouped in any manner desired on to various dynamos. This arrangement is necessarily a very imperfect one, because, as the demand for current on each of these supply lines varies, the attendant in charge of the station has to effect changes in the grouping of these circuits on the different dynamos, and this can hardly be done without a momentary "wink" or extinction of the lights. Except that they are gathered together in the same station, the dynamos so worked have no connection with one another, and the arrangement is virtually a collection of little central stations arranged for the sake of convenience under one roof.

The other arrangement is that of parallel worked alternators, and is the only plan on which alternating-current dynamos in Electric Stations intended for the permanent supply of lighting current should be arranged.

Before 1884 it may be said that the general opinion of electricians was that alternating current machines could not be worked together in parallel. Mr. Wilde had, however, published in the *Proceedings of the Literary and Philosophical Society, Manchester*, on December 15th, 1868, a Paper, which was reprinted in the *Philosophical Magazine* for January, 1869, in which he fully described experiments on the simultaneous working of two or more alternate current machines connected together in multiple arc. These observations were lost sight of until, in 1883, Dr. Hopkinson again drew attention to the subject in a lecture delivered before the Institution of Civil Engineers in 1883, and also more fully in a Paper published in the *Proceedings of the Society of Telegraph Engineers* on November 13, 1884, he proved that alternate current machines could certainly be worked together in parallel and, on the other hand, could not be worked together when coupled in series. Dr. Hopkinson's proof to this is as follows:—

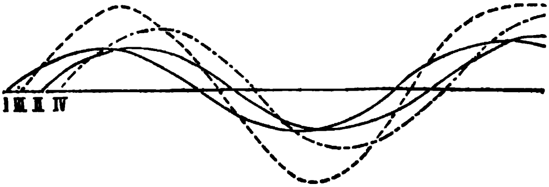


FIG. 7.

"Suppose two alternators coupled in series, the resultant electromotive force of the circuit will be the sum of the electromotive force of the two machines. This resultant electromotive force may be represented by a dotted curve as in Fig. 7; the two firm lines curves I. and II. representing the separate electromotive force curves of the two machines; the ordinates of the dotted curve III. being the sum of the ordinates of the two firm line curves. Let the broken line curve IV. represent the resultant current in the circuit, this will therefore lag behind the resultant electromotive force curves in phase. The power being exerted by each machine at any instant is represented by the product of the current and the electromotive force, and it is clear that as a phase of the current is more near to the phase of the lagging machine, II., than to that of the leading machine, I., the lagging machine must do more work in producing electricity than the leading machine and consequently its velocity will be retarded, and this retardation will go on until the two machines settle down into exactly opposite phases, when no current will pass; accordingly, two alternators, coupled in series and independently driven, adjust themselves so that the resultant current in the external circuit is zero; in other words, they neutralize each other if driven in series. As a corollary to this, it follows that two alternators coupled together in parallel will mutually tend to bring one another into step. Let A B, Fig. 8, represent the two terminals of one alternate current machine, and *a b* the two terminals of another machine independently driven. Let A and *a* be connected together and B and *b*. So regarded, the two machines are in series, and we have just proved they will exactly oppose each other's effects, that is, that when A is positive, *a* will be also positive, and when A is negative, *a* is also negative. Connecting A and *a* through the comparatively high resistance of the external circuit with B and *b*, the current passing through that circuit will not in any way disturb the relations of the two machines; hence, when A is positive, *a* is positive, and when A is negative, *a* is negative, which is the condition required that the two machines can work together in parallel and send a current into the external circuit."

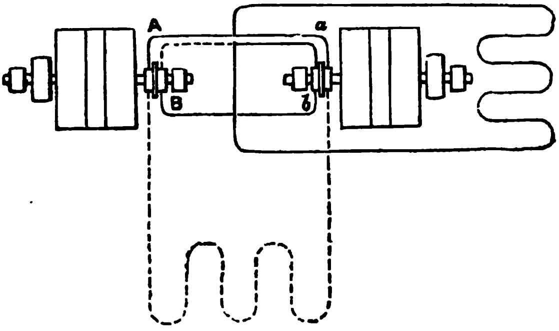


FIG. 8.

Dr. Hopkinson was therefore able to predict from this line of reasoning that there would be no difficulty in coupling a number of alternate current machines on to one external circuit in parallel, a little care being taken that the machines were put together only when they had attained something like the proper velocity. The analytical proof that when two machines are so coupled the leading machine does most work was also given by Dr. Hopkinson in the Paper quoted, as follows:

Let two alternators of equal size and electromotive force be coupled in parallel on to one circuit. At any instant let the electromotive force of one machine be e_1, and that of the other e_2; and let the electromotive forces of the two machines differ in phase, so that we can express e_1 and e_2 by the expressions

$$e_1 = \mathrm{E} \sin (p t + a)$$

and

$$e_2 = \mathrm{E} \sin (p t - a).$$

Hence, E is the maximum value of the E.M.F. of either machine, and $2a$ is the phase angle difference between e_1 and e_2. Let the current at the same instant proceeding from each machine be called i_1 and i_2, and let $2r$ and $2l$ be the resistance and inductance of each machine and R the resistance of the external circuit. Then the current equations for the circuit of the two machines are respectively

$$2l\frac{d i_1}{d t} + 2 r i_1 = \mathrm{E} \sin (p t + a) - \mathrm{R}(i_1 + i_2) \quad . \quad \text{(i.)}$$

$$2l\frac{d i_2}{d t} + 2 r i_2 = \mathrm{E} \sin (p t - a) - \mathrm{R}(i_1 + i_2) \quad . \quad \text{(ii.)}$$

Adding and subtracting (i.) and (ii.) we get

$$l\frac{d}{d t}(i_1 + i_2) + (r + \mathrm{R})(i_1 + i_2) = \mathrm{E} \sin p t \cos a \quad . \quad \text{(iii.)}$$

$$l\frac{d}{d t}(i_1 - i_2) + r(i_1 - i_2) = \mathrm{E} \cos p t \sin a \quad . \quad \text{(iv.)}$$

Solving (iii.) and (iv.) we get

$$i_1 + i_2 = \frac{\mathrm{E} \cos a}{(r + \mathrm{R})^2 + p^2 l^2}\{(r + \mathrm{R}) \sin p t - p l \cos p t\} \quad \text{(v.)}$$

$$i_1 - i_2 = \frac{\mathrm{E} \sin a}{r^2 + p^2 l^2}\{r \cos p t + p l \sin p t\}. \quad . \quad . \quad . \quad \text{(vi.)}$$

The electrical work done in one second by the leading machine is w_1 and

$$w_1 = \frac{1}{T}\int_{t=0}^{t=T} \tfrac{1}{2}\,E\sin(p\,t+a)\,\{i_1+i_2+(i_1-i_2)\}. \quad \text{(vii.)}$$

T being the time of the complete period or $2\pi/p$. Also the work done per second by the following machine is w_2, where

$$w_2 = \frac{1}{T}\int_{t=0}^{t=T} \tfrac{1}{2}\,E\sin(p\,t-a)\,\{i_1+i_2-(i_1-i_2)\}. \quad \text{(viii.)}$$

Taking the values of i_1+i_2 and i_1-i_2 from (v.) and (vi.) and inserting them in (vii.) and (viii.) and performing the multiplications and definite integrations, we arrive at the values for w_1 and w_2 as follows:—

$$w_1 = \tfrac{1}{4}\,\frac{E^2}{(r+R)^2+p^2\,l^2}\{(r+R)\cos^2 a - p\,l\sin a\cos a\}$$
$$+\tfrac{1}{4}\,\frac{E^2}{r^2+p^2\,l^2}\{r\sin^2 a + p\,l\sin a\cos a\}. \quad . \quad . \quad \text{(ix.)}$$

Substituting and integrating in the same way (viii.) we have for the value of w_2,

$$w_2 = \tfrac{1}{4}\,\frac{E^2}{(r+R)^2+p^2\,l^2}\{(r+R)\cos^2 a + p\,l\sin a\cos a\}$$
$$+\tfrac{1}{4}\,\frac{E^2}{r^2+p^2\,l^2}\{r\sin^2 a - p\,l\sin a\cos a\}. \quad . \quad . \quad \text{(x.)}$$

A little consideration will show that w_1 is always *greater than* w_2, in other words, the leading machine does most work. If, therefore, one machine lags in phase behind the other, the lagging machine is relieved of its load, and the motor, *unless too well governed*, will bring it up into step again.

The conditions for best mutual control are also obtainable from the values of w_1 and w_2; for subtracting (ix.) and (x.) we get

$$w_1 - w_2 = \frac{E^2}{8}\left\{\frac{p\,l}{r^2+p^2\,l^2} - \frac{p\,l}{(r+R)^2+p^2\,l^2}\right\}\sin 2a \quad . \quad \text{(xi.)}$$

The machines are doing the maximum difference of work when $a = 45°$, and then the following machine is doing no work as a generator. If the difference of phase is then still further increased, the following machine becomes a motor and absorbs work.

The best conditions for mutual control are, then, that such relations between r, $p\,l$, and R should hold good that for a small value of a—that is, when the machines are just beginning to get out of step—the quantity in (xi.) in brackets shall have a maximum value. The difference of the work done by the alternators is a periodic quantity as regards a, and the value of this difference for small values of a is greater in proportion as the expression

$$\frac{p\,l}{r^2+p^2\,l^2}-\frac{p\,l}{(r+\mathrm{R})^2+p^2\,l^2} \quad . \quad . \quad . \quad \text{(xii.)}$$

is greater.

Let R be infinite—that is, suppose the external circuit is open, then it is easily seen that (xii.) has a maximum value when

$$r=p\,l \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad \text{(xiii.)}$$

Hence the best condition for mutual control of the machines is that the ratio of armature resistance to armature inductance shall be about equal to 2π times the frequency of the alternations.

Moreover, if $r=p\,l$ and $\mathrm{R}=\infty$ then the value of (xii.) is reduced to $\frac{1}{2r}$, and this is greater in proportion as r and therefore $p\,l$ is small. Hence this analytical treatment points to the conclusion that the best conditions for mutual control of the two alternators—that is, the condition under which they will best resist getting out of step, is that both the inductance and resistance of the armature circuit should be small, and that their ratio should have the value defined by equation (xiii.).

§ 6. **Parallel Working of Alternators.**—These predictions of Dr. Hopkinson as to the practicability of parallel working were shown to be capable of fulfilment in some experiments made in 1884, in conjunction with Prof. W. G. Adams on the De Meritens alternators at the South Foreland Lighthouse, which were run together successfully in parallel and also as motors. At the time when these experiments were made, alternating current working had hardly begun to assume a practical form, and hence, although scientifically interesting, these experiments hardly received the attention they deserved from dynamo manufacturers.

In the following five years, transformer work was practically developed, and in May, 1889, Mr. W. M. Mordey read a very important Paper before the Institution of Electrical Engineers, in which he discussed, with great thoroughness, the whole question of parallel working of alternators, and described some remarkable experiments with his own alternators, which exhibited the power of parallel working in a remarkable degree. In this Paper Mr. Mordey expounded with great clearness the condition of practical parallel working.

Before the date of this Paper, engineers had, however, become convinced that the parallel working of alternators in transformer stations was a matter of the highest importance; but very varied opinions had been expressed as to the conditions and constructions of alternators, which would enable this parallel working to be most successfully achieved. Generally speaking, it may be said that between the years 1884 and 1889 it had been generally recognised that parallel working of alternators could be accomplished; but it was hardly felt that the arrangement was one which could be completely and thoroughly depended upon in every case, and, moreover, entire confidence was not felt in the ability of every form of alternator to be so used. Some had expressed the opinion that alternators could be successfully run in parallel if the armature circuits had a good deal of self-induction, in other words, if they had iron cores.

In a Paper on alternate current machinery, Mr. Kapp* dealt at considerable length with this part of the subject. Referring to alternators with armature circuits of small self-induction, Mr. Kapp said machines of this type could only be run in parallel if the strength of their field is adjusted with almost mathematical precision. To make them fit for this method of working the armature resistance or armature self-induction must be increased. Further down he says it is well known that alternators having no iron in their armatures cannot be run in parallel except by the adoption of some such expedient as a choking coil, in series with the armature.

Practical experience, therefore, had been conflicting as to the exact circumstances under which parallel working could be most easily and safely accomplished. It had been shown before the date of Mr. Mordey's Paper that the Zipernowsky alternator, working at a low frequency of 42, and which had an iron-cored armature, could work well in parallel, but this seemed rather to support the theory that self-induction in the armature was useful for this purpose.

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* See *Proceedings of the Institution of Electrical Engineers*, February, 1889.

The Westinghouse Company had tried working their alternators in parallel, and had apparently found that the machines controlled one another well under full load, but could not be depended on to do so at light loads.

The Lowrie-Hall alternators, which had iron-cored armatures, had also been shown to be capable of being worked in parallel together.

Experience, therefore, as far as it went, seemed to indicate that machines with iron-cored armatures would work together in parallel; but in the Paper referred to, Mr. Mordey described some remarkably interesting experiments with his alternator, which, as we have seen, is without iron in the armature, and in which he obtained very novel results on the coupling together of alternators both at the same and at different electromotive forces. In these experiments, each alternator was driven by a separate 75 horse-power Fowler engine, the speed of working being 120 per minute. The following experiments were tried and described, and subsequently demonstrated in public by Mr. Mordey. First, the alternators were run up to full speed, and each excited to give 2,000 volts. When the phases were identical, as determined by synchronising transformers and lamps, the machines were put into parallel, without any external load and without any impedance coils or resistance coils between them; they ran in parallel perfectly. Second, a suitable inductionless load was then put on and taken off; they ran well, under the circumstances. Third, they were then uncoupled and the load being connected to the mains, they were suddenly and simultaneously switched on without synchronisation; and they pulled each other into parallel at once. Fourth, one of the alternators was excited to give 1,000 volts, and the other 2,000, they were then switched in parallel; and they went into step immediately, giving a resultant electromotive force of about 1,500 volts. Fifth, when one machine was excited to 1,000 volts and the other to 2,000 volts, they were switched in parallel when out of phase, and instantly went into step, a large current appeared to pass between them for a fraction of a second. Sixth, whilst running in parallel, one machine was disconnected from the engine; it continued to run as a motor. Seventh, two machines were then coupled up to 2,000 volts, they were then switched in parallel when out of step, and without any external load; and went into step instantly. Eighth, whilst running as in the last case, the steam from one engine was shut off; the alternators kept in step, one acting as a dynamo and driving the other as a motor and its associated engine.

It was found that the machines could also pull each other into step even when running at somewhat different speeds; accordingly, these machines in which the armature had small resistance and, relatively speaking to other machines, small self-induction, worked together in parallel under very trying circumstances, and showed a great power of mutual control. This was sufficient to demonstrate the incompleteness of ideas previously prevalent.

Since the date of Mr. Mordey's Paper Mr. Ferranti has also been successful in working his alternators in parallel, the 625 horse-power alternators at Deptford being worked regularly in parallel, and the 1,250 horse-power alternators working at 10,000 volts being found to be capable of being worked in parallel with the 625 horse-power alternators working at 2,400 volts, having the pressure raised to 10,000 volts through step-up transformers.

It is, therefore, evident that successful parallel working is in no way dependent upon iron in the armature core, nor upon external self-induction, but that the cause which contributes to produce successful parallel working must be looked for in other directions.

Mr. Mordey first gave the demonstration of the perfection of parallel working attained by the employment of alternators of small armature resistance and inductance, and he took up the position that a perfect alternator for every purpose should have no resistance in its armature and no self-induction. Very briefly, Mr. Mordey's theory of the conditions of synchronous control of alternators may be said to be that the armature circuits should have such small impedance that the currents in them can be rapidly reversed, and that very small impressed electromotive forces may give rise to large currents flowing through the armatures; also that the prime motors or engines should be under the control of the dynamos, and should not be too well governed, or not governed at all. Under these circumstances, if one alternator lags behind the other in consequence of its speed slightly falling off, its electromotive force is diminished, and the leading machine sends a reversed current through the armature of the lagging machine, converting it into a motor, and accelerating it into step again, provided that the moving parts of its associated engine are not too slow moving and massive to respond quickly to this impulse.

The absence of armature self-induction and resistance permits, therefore, a large controlling current to be applied to the lagging machine to bring it up into step. The falling off in the work done by the lagging machine as soon as it begins to lag, causes the engine driving it to speed up, and hence the lagging machine is brought up into line again, both by the engine pushing it and the leading machine pulling it, and this process of forcing it into step with the other is applied promptly and powerfully the moment there is the slightest falling off in speed in either of the machines. Hence results a synchronising mutual control, which is automatic and prompt. Self-induction or resistance in the armature circuit is injurious because it causes a diminution and delay in the application of this restoring force.

There is one other element which also contributes to the constant adjustment of equality in the speeds and electromotive forces, and that is the re-action of the armature currents upon the field magnets. Mr. Swinburne has emphasised very strongly the importance of this element in the process.

As is well known, the action of the armature current upon the field magnets, when the machine is acting as a generator, is to weaken the fields. Consider the case of a Ferranti alternator. The instant of maximum impressed electromotive force in any coil during the phase is when that armature coil is half way between the positions in which it is exactly opposite to a magnet pole. This is the instant when the rate of change of induction through the coil is a maximum.

Owing to the presence of some small self-induction in the armature circuit, the current lags in phase a little behind the impressed electromotive force, and the current has its maximum when the armature coil is more nearly opposite to the middle of a magnet pole. A little consideration will show that the direction of the current in the armature is such that it tends to diminish the magnetism of that magnetic pole. If the armature current is reversed when the coil is in that position, it will, on the other hand, tend to increase or strengthen the magnetism of the field pole. This armature reaction has the effect of strengthening the field poles of the machine which lags, and hence tends to increase its electromotive force. This strengthening of the field of the lagging machine still further increases the forces brought to bear upon the armature to bring it up into step with the other. In such an alternator it would seem that there are, therefore, three causes at work tending to maintain synchronism when worked in parallel with another similar machine.

First, the lagging machine does less work, and the engine therefore gathers speed, and being relieved of load will, unless too well governed, accelerate the speed of the lagging machine. Second, the leading machine impresses a reverse electromotive force on the lagging machine, and will, unless the armature resistance and inductance are too great, send through it a considerable back current, and convert the laggard into a motor. Third, the armature reaction comes into operation to strengthen the magnetic field of the laggard, and increases the force of restitution on the armature. Perfect parallel working for practical purposes requires that these actions shall be very prompt —that is, that neither machine shall get out of step by more than a very small fraction of the whole phase without being checked. Hence the greater the self-induction of the armature circuit the slower must be the frequency of the alternations in order to effect parallel working well, because there is then a longer period of time at disposal in which to create a rectification of phase before mischief is done. The perfection of parallel working requires that the machines should control each other equally, whatever the value of the current in the external circuit.

Mr. Mordey's alternators do this in a very perfect manner. Two of these alternators can be thrown into parallel with no external load equally as well as when fully loaded up. Two alternators so coupled should control one another without much actual exchange of current. It is easy to test whether this is the case by placing an ammeter on the armature circuit of each machine, and one ammeter on the omnibus bars to measure the total current. When the machines are running well in parallel the separate armature currents should be equal in total value to the total current. The needles of the ammeters on each machine should also be steady, and not vibrate much, indicating the existence of rapid fluctuations in the current in each armature.

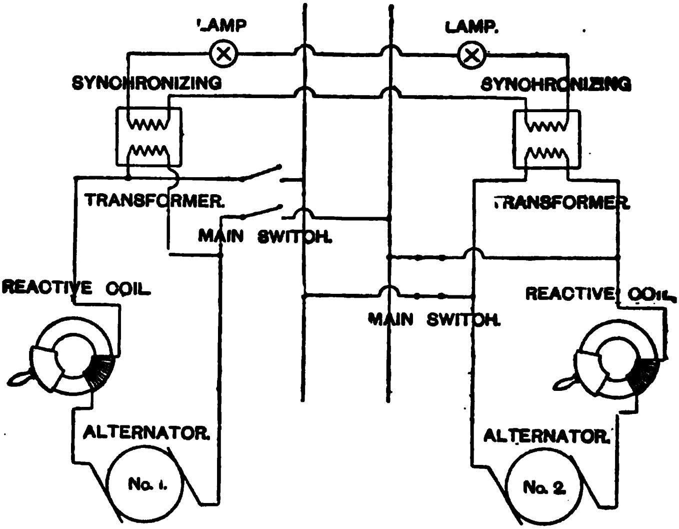

FIG. 9.—Arrangement of Reactive Coils used in putting Thomson Alternators in Parallel.

The Thomson-Houston Company insert a reactive coil in series with the armature circuit of the dynamo which is to be put in parallel with others. This reactive coil is only a variable impedance coil (*see* Fig. 104, Chap. II.), which is useful to prevent great rushes of current taking place through the armature of the incoming machine, and which impedance is removed when the machine is in step with the others (*see* Fig. 9).

The use of this reactive coil may be thus described: When two or more alternators are worked in parallel on to the same omnibus primary main, as is the case with the Thomson alternators at St. Brieux, in France, a reactive coil is inserted in the main circuit of each machine. When one alternator is working on the circuit, and it is required to insert another in parallel with it, the incoming machine is first brought up to the same voltage as the working circuit. It is then synchronized by means of the synchronizing transformers and lamps, as described in § 9 of Chapter II., and the reactive coil is turned so as to insert the whole of the self-induction in the armature circuit of the incoming machine. When the volts and speed of this last machine are adjusted, the double pole-switch is closed, and the self-induction gradually removed. By this means any sudden back-rush of currents into the incoming machine is avoided, and also any outrush; the load can be gradually divided between the two alternators by adjusting their exciting currents or speeds, and thus obviate any disturbance of the lighting current.

In the case of the Ganz alternators it is found desirable to run up the incoming machine on a bank of separate lamps to nearly the same volts and amperes as the machine will have when on the working circuit, and then to put in the machine and remove the artificial load. This last arrangement seems necessary only with alternators of considerable self-induction, and in which the variation of terminal volts with armature current is considerable. With machines in which the "drop" between no load and full load is negligible this artificial load is not necessary.

The ease of parallel working is undoubtedly assisted by employing a moderate frequency of alternation. At present the frequencies now in use are by Zipernowsky, 42 ∿; Mordey, 100 ∿; Elwell-Parker, 80 ∿; Ferranti, 83 ∿; Westinghouse, 133 ∿. The symbol ∿ was introduced by Mr. Mordey to denote one complete alternation or period or wave of current.

In addition to this, the engine speeds are also a factor in promoting facility of synchronisation. A slow moving engine with heavy fly-wheel is less advantageous than an engine having a moderately rapid piston speed and a not very massive fly-wheel for the parallel working of alternators. The reason for this being that the slow moving engine is only, at comparatively great intervals of time, giving a push to the alternator, and it is not therefore ready at any instant immediately to respond and act on a lagging armature, in the way above described. It will also be evident, from remarks already made, that the governing of the engine has a certain share in effecting good parallel working. If the government of the engine was theoretically perfect, it might, in one way, prevent alternators from getting out of step, but it would prove a disadvantage in controlling the engine from making the little spurt necessary to restore co-phasal working when they do get out of step. What seems to be required is a governor that should not be too good, that it should be one which allows a margin of racing in the engine, in order that it may pick up any lag in the alternator; but which is good enough to control the average speed under varying external load.

§ 7. **Conductors employed in Transformer Systems.**—Conductors for electric lighting purposes by alternating currents may be either underground or aerial conductors. They are spoken of as extra high, high or low pressure conductors according to the voltage of the current. This division, of course, is perfectly arbitrary, but for the purpose of legislation the English Board of Trade have defined a low-pressure conductor when used with alternating currents, to be a circuit such that the difference of pressure between the lead and return wires is the equivalent of 150 volts. A difference of potential on the alternating-current system is deemed to be the equivalent of a difference of potential on the continuous-current system when those pressures produce an equal heating effect if applied to the ends of a thin stretched wire or carbon filament. A high-pressure conductor is defined to be a conductor between the lead and return of which a greater difference of pressure exists than 150 volts. An extra high pressure is defined to be a pressure greater than 3,000 volts.

High-pressure conductors for the purpose of electric lighting by alternating-current systems require exceedingly careful insulation; and many systems for the insulation of such conductors, both for high and extra high pressures, are now in use, some of which have been described in the foregoing sections. The use of overhead high-pressure conductors is not encouraged by the Board of Trade, and they have laid down stringent regulations as to the manner in which such aerial conductors shall be erected and maintained. Speaking generally, when overhead conductors are used for high-pressure distribution, these consist of some form of highly insulated stranded copper conductor, either 7/20, 7/18, 7/16, or 19/18, which is suspended from a standard steel stay line or bearer of 7/16, both the conductor and the stay line being insulated preferably by fluid insulators such as those shown in Fig. 6, the cable being suspended from the stay line by rings and leather thongs at short intervals (*see* Fig. 10).

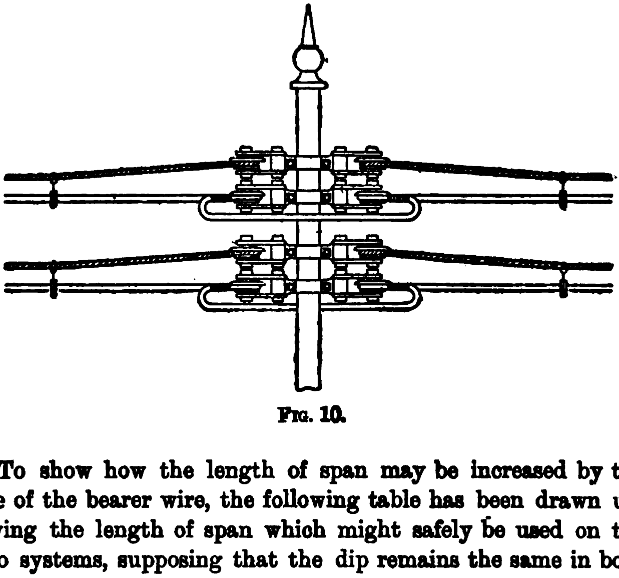

FIG. 10.

To show how the length of span may be increased by the use of the bearer wire, the following table has been drawn up, giving the length of span which might safely be used on the two systems, supposing that the dip remains the same in both cases, and that a wind pressure of 20lb. is allowed for :—

Conductor. No. of strands.	Dip.	Allowable span.	
		Without bearer.	With 7/16 bearer.
	feet.	feet.	feet.
7/20	5	64	238
7/18	5	80	230
7/16	5	102	220
19/18	5	118	210

When passing through towns, the Board of Trade require that the conductors in any street shall not be of a less height from the ground than 30ft., where they cross the street, or go within 6ft. of any building or erection other than the support for the conductor. Spans between the supports are not to exceed 200ft. for straight runs, or 150ft. for curves. Every support or pole, if of metal, is to be connected to the earth, and if of wood to have an efficient lightning conductor connected to it, of approved pattern. Every high-pressure aerial conductor controlled by these regulations for public supply must be continuously insulated with a durable and efficient material, to be approved by the Board of Trade, of a thickness of not less than $\frac{1}{10}$th part of an inch, and in cases where an extreme difference of potential exceeds 2,000 volts, the thickness of insulation must not be less in inches or parts of an inch than the number obtained by dividing the number representing the volts by 20,000. This insulation must be further efficiently protected on the outside against injury by removal or abrasion. The material used for insulating the high-pressure aerial conductors is preferably the best vulcanised rubber covering, overlaid with a protecting covering; but the Board of Trade Rules permit the use of any material, provided that it is not liable to injurious change of structure when exposed to any temperature between 10° and 150° F., or by contact with the ordinary atmosphere of towns or manufacturing districts.

The maximum working current in any aerial conductor is defined to be one which will not raise the temperature of the conductor in any part to a greater extent than 30°F.

In erecting such aerial conductors, where desirable and permitted, it is necessary that the lead and return conductors should not be distant from one another by more than, say, 12in., in order that the inductive effect of the alternating current flowing in them may not produce any disturbances in neighbouring telephone wires.

In a case where aerial conductors have been erected by supply companies in Great Britain, who afterwards take a Provisional Order for that district of supply, the local authorities have the right to require the removal of the overhead conductors within two years after the date of the Order if they think fit. When, however, the local authorities permit the continuance of such conductors, they have to be erected and maintained under the Board of Trade Rules, to which reference has just been made. Although there are conditions under which the use of such overhead conductors is desirable for economical reasons, there is little doubt but that the only permanently satisfactory method of supply is by underground conductors.

In designing |the conductor system for a transformer station there will in general be two sets of conductors which have to be provided, the high-pressure conductor system conveying the primary current from the generating station to the transformer centres, and the low-pressure distributing conductors which convey current to the premises of consumers. With regard to underground high-pressure conductors, broadly speaking, there are three systems in use.

In the first, some form of highly insulated cable is drawn into well-scoured iron or earthenware pipes. In laying down a system of this kind, the roads and pavements are first opened up in sections, and the pipes laid with brick-built drawing-in boxes at bends and every 80 or 100 yards in straight runs. In laying down the pipes an iron wire is run through them, by means of which the cables are drawn in subsequently. On the completion of the pipe-laying, highly-insulated conductors, most generally insulated with the best vulcanised india-rubber, and with an additional protecting covering, are drawn in. In cases where the insulating material consists of some fibrous vegetable matter, impregnated with insulated material such as oil, resin, or bitumen, it is necessary that the cable should be further protected by a continuous lead covering drawn on to it, and the lead itself further protected by coverings of tarred hemp. In some cases a number of cables are drawn in together to the iron pipe, or bunched as it is called. This is not, on the whole, a desirable proceeding, the cables necessarily get matted together, and the withdrawal of any one of the number subsequently is often a matter of great difficulty, if not impossibility. In winter, water may get access to the pipes and freeze, binding together the cables in such a way that they cannot be separated without drawing out the whole bunch. Whenever iron pipes are employed, by far the best way is to have one pipe for each cable, selecting the pipe of such size that the cable could easily be drawn in and out. In some cases, instead of using iron or stoneware pipes, conduits formed of cement or bitumen concrete have been employed. In these cases the conduit consists of a mass of material, which is pierced with channels or ways, in each of which insulated cable is drawn, suitable drawing-in boxes being built at intervals. There is no question that such entire separation of high-pressure cables is desirable; if cables are bunched together, then a fault in one is very liable to extend to others at the same spot, disturbing a whole group of conductors. When the separate drawing-in system is employed, each conductor can be removed for examination and replaced separately.

Secondly, in opposition to these drawing-in systems, there are the systems in which insulated cables are imbedded in some solid insulating material, or drawn into pipes which are filled with heavy oil. The best known of these systems is that adopted by the Callender Bitumen Company, of laying fairly well insulated cables in iron troughs, which are subsequently poured in and sealed with natural asphalte on bitumen. In this system a series of iron troughs about 6in. wide and 4in. deep, are laid down in the roadways and streets. Bearers of wood, impregnated with bitumen or other insulating material of the shape shown in Fig. 11, are then placed in the troughs, at intervals of 18in. or 2ft. The cables are then laid in the troughs on these bearers and carefully strained out, the bearers keeping them in position. When a sufficient length of the cable has thus been laid and stretched, the trough is poured full with melted bitumen or natural Trinidad asphalte, and on cooling the cables are set fast in the interior of the solid mass;

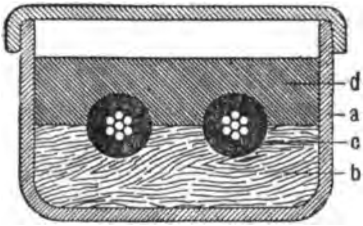

FIG. 11.—Section of Iron Troughing, a, showing Cables, c, carried on Wooden Bearer, b, and set solid in Bitumen, d, as laid on the Callender System for High-Tension Cables.

an iron lid is then put on the trough, and the roadway filled in. At intervals, junction boxes are provided, at which off-sets can be taken, and when the joints are made in these boxes they are likewise filled in with melted bitumen. Experience has so far shown that this system is a satisfactory method for insulating cables with pressures not exceeding 2,000 volts, and that if the work is carefully and properly carried out, it affords a permanently satisfactory method of insulating high-pressure cables.

Another method of laying and insulating high-pressure cables is one that has been for many years advocated by the late Mr. David Brooks, and is now carried out by Messrs. Johnson and Phillips, of London. Under this method, a system of wrought-iron piping is laid down, and a cable is drawn in, consisting of a copper-stranded conductor covered with a covering of jute or hemp. This hemp-covered conductor is first thoroughly desiccated and boiled in resin oil, so as to impregnate the fibres thoroughly with the insulating oil. This impregnated cable being drawn into the iron pipe, the pipe is filled up with the same insulating oil, forced into it from the lowest level. Allowance is made for the expansion of the oil and difference of level by means of stand pipes which maintain the hydraulic pressure of the oil in the pipe. This method of fluid insulation has not yet been widely used, but, having regard to the success which has attended the use of oil as an insulating material in the case of transformers, there is good reason to believe that a properly worked-out system of fluid insulation for high-pressure conductors would be one which would be attended with great success. The immense advantage of a fluid insulator is that it cannot be permanently cracked by a spark, but heals up after a discharge has passed.

The third system of insulation which has been so far adopted for high and extra high pressures is that of concentric stranded or solid tubular conductors, the insulating material between the conductors being either paper impregnated with various waxes, as used by Mr. Ferranti, and fully described in a former section, or the Siemens Concentric Cable, which has been described in § 7 of Chapter II. of this volume. Other makers, such as the Fowler-Waring Company, also supply high-pressure concentric cables, insulated with jute impregnated with resinous or oily material.

In selecting the proper size and form of cable to be used with alternating current, it is necessary to take into consideration the fact referred to in Vol. I., § 11 of Chapter IV., in which it is pointed out that the flow of alternating current is practically confined to a certain external layer of the conductor when this last is above a certain size, and that the diameter of any conductor which can be economically employed for alternating currents is determined by the periodicity of that current. In the section referred to, it has been shown that the effect of the periodicity of the current is practically to increase the resistance of the conductor in consequence of the fact that the current flow takes place in the outer layers of the conductor.

In the case of continuous currents, or currents having a very slow rate of alternation, the distribution of the current is uniform over the cross-section for any practical size of conductors. On the other hand, as the rates of alternation increase, the current is more or less limited to the outer layers of the metal, and the resistance of the conductor is therefore increased, because the central portions of the conductor are, as it were, not used by the current, and might, therefore, just as well be absent. Lord Rayleigh has given, as previously stated, a formula by which such increase of resistance could be stated; and Mr. Mordey, working from the calculations given by Sir William Thomson, gave in his Paper on "Alternate Current Working" a table showing the increase of resistance over and above the true ohmic resistance of the conductor, calculated for various frequencies and on the basis that the density of current is taken at 450 amperes per square inch. Such a current density gives a loss of 1 per cent. per mile. with 2,000 volts; it also gives about 1 per cent. loss per 100 yards with 100 volts, or more exactly 1·5 per cent. In the table on page 371 the increase of resistance for conductors of different sizes is given for three different frequencies: 80, 100 and 133.

The first two columns give the diameter of the conductor, the second two columns its sectional area, the fifth column gives the amount as a percentage by which the virtual resistance of the copper conductor for that frequency exceeds the true steady or ohmic resistance of that conductor. The sixth column gives the current flowing in the conductor. It will be seen, therefore, that at the frequency of 80 for conductors of less than half an inch in diameter, the increase in resistance due to frequency is negligible, or at any rate something less than 2½ per cent. For conductors, 1in. in diameter and upwards, the increase in resistance due to the non-uniform distribution of the current over the cross section of the conductor becomes very serious even for a frequency of 80, and hence, the practical deduction from this is that in no case should a copper conductor, intended for the conveyance of alternating currents, have a thickness or diameter greater than half an inch, and preferably rather less than that.

Table *showing Percentage Increase of Resistance in Conductors (copper) of various diameters employed with Alternating Currents of various frequencies.*

Diameter of copper.		Area of cross-section.		Increase over ordinary resistance.	Current at 450 amperes per sq.in.	Watts at 2,000 volts	Watts at 100 volts.	∽ per second.
MM.	Inch.	Sq. mm	Sq. in.					
10	·3937	78·54	·12	Less than $\frac{1}{100}$ %	55	110,000	5,500	80
15	·5907	176·7	·274	2½ %	133	266,000	13,300	
20	·7874	314·16	·487	8 %	220	440,000	22,000	
25	·9842	490·8	·760	17½ %	...	...	...	
40	1·575	1,256	1·95	68 %	...	...	...	
100	3·937	7,854	12·17	3·8 times	...	...	...	
1,000	39·37	785,400	1,217	35 times	...	...	...	
9	·3543	63·62	·098	Less than $\frac{1}{100}$ %	45	90,000	4,500	100
13·4	·5280	141·3	·218	2½ %	98·5	197,000	9,850	
18	·7086	254·4	·394	8 %	178	356,000	17,800	
22·4	·8826	394	·611	17½ %	...	...	...	
7·75	·3013	47·2	·071	Less than $\frac{1}{100}$ %	32	64,000	3,200	133
11·61	·4570	106	·164	2½ %	74	148,000	7,400	
15·5	·6102	189	·292	8 %	131·4	263,000	13,140	
19·36	·7622	294	·456	17½ %	...	...	...	

This virtual resistance effect will not be found to be at all important in high-pressure conductors, the limitations imposed by the amount of energy which it is safe to convey through the single cable will generally render it necessary to keep down the diameter of the cable below the point at which the virtual resistance effect is sensible; but for the low-tension secondary conductors working at 100 volts, it is necessary to avoid the use of conductors of a greater diameter than half an inch. This is generally not difficult to do and can always be attained by using a multiplex cable instead of one single thick one. The same remarks of course apply to concentric tubular conductors, whether constructed with solid tubes or with stranded conductors; in any case a thickness of metal greater than half an inch should be avoided for frequencies in the neighbourhood of 80 to 100. Where higher frequencies are used it will be essential to employ conductors of much less diameter and thickness. Thin insulated strips of copper would have to be employed for frequencies of 200 and upwards in order to avoid serious waste of material.

§ 8. **Effect of Alternating-Current Flow through Concentric Cables.**—In the distribution of alternating currents by conductors in which the lead and return are separate cables, there is great risk of producing inductive disturbance in telephone and telegraph wires even at considerable distances. The only method by which absolute immunity from such disturbance can be secured is by the employment of concentric cables in which the one conductor wholly encloses the other. These conductors, which may be called the inner and outer members, may be copper concentric tubes, or stranded cables in which the inner member is a simple strand of naked copper wires insulated and overlaid by an enclosing cylindrical strand which forms the outer member. Cables of this kind can be employed with alternating currents of any strength and cannot produce any inductive disturbance on other wires, because there is no external magnetic field in the case of the concentric cable. On the other hand, such concentric cables possess very marked electrostatic capacity, and which generally seems to be something like one-third of a microfarad per mile between the inner and outer members. There are, in fact, two capacities to be considered—the capacity between the inner and outer members or conductors, and the capacity between the outer conductor and the earth. The last is always greater and sometimes much greater than the former. The capacity between the inner and outer members can be calculated from the well-known formula for the electrostatic capacity of two co-axial cylinders. If R_2 is the radius of the circular cross-section of the exterior of the inner tube, and R_3 is the radius of the cross-section of the outer tube, then the electrostatic capacity for a length l of the condenser formed of these two concentric co-axial cylinders is given by the formula

$$C = \frac{K\,l}{2 \log_e \frac{R_3}{R_2}},$$

where K is the specific inductive capacity of the dielectric between the cylinders. The capacity will be given by the above in absolute electrostatic units; but if l, R_2, and R_3 are measured in centimetres the multiplication of the above by $\frac{1}{9 \times 10^{11}}$ will reduce it to capacity in farads, or $\frac{1}{9 \times 10^{5}}$ to microfarads. For example, the ratio of R_3 to R_2 in the case of the ¼-inch section Ferranti main is $R_3/R_2 = 2{\cdot}27$, and the capacity per mile run is ·367 microfarads; taken between the inner and outer. The capacity between the outer copper and the iron tube is nearly ten times greater. When such concentric cables are employed for the transmission of alternating currents peculiar effects of rise of electric pressure often make themselves felt which depend on the fact of the sensible capacity of the mains. In fact, concentric cables behave very much as if they consisted of a pair of non-capacious mains, or mains without capacity, bridged across by a condenser or condensers. The combination and reaction of this capacity on the self-induction of the generating apparatus and the reaction of the condenser back-electromotive force on the field-magnets of the generator produce effects peculiar to the case, which need to be understood by those concerned in dealing with such systems of conductors. In order to understand the nature of these effects it is necessary to examine the peculiarities of the current flow in the simplest possible case, viz., when an alternator acts through an inductive line, or is connected to a pair of leads which we shall primarily suppose to be without capacity but which possess resistance and self-induction and which are joined across by a condenser of known capacity shunted by an inductive resistance. We may then pass on to consider the nature of similar effects when the capacity is supplied by a concentric cable connected to any alternator or transformer.*

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* These problems have been treated by geometrical methods by Mr. Blakesley in his book on "Alternating Currents," to which we refer the reader.

Let A (Fig. 12) be an alternator connected to an inductive circuit, *a b f*, of which the section *a b* has inductance L and resistance R, and the section *b f* has inductance *l* and resistance *r*. At *b* let a condenser of capacity C be inserted, and let the terminals, *e*, *d*, and *f* of the line, condenser, and alternator be to earth.

Let v_0 be the potential at *a* at any instant, and v_1 that at *b*; and let V_0, V_1, be the maximum values of these potentials, supposed to vary harmonically. Let i_1 and i_2 be the currents at any instant in the sections of the line *a b*, *b f*, and *i* the current flowing into the condenser, and let I_1, I_2, I, be the maximum values of the same. Under these circumstances we proceed in the first place to investigate analytically what are the relative values of V_0 and V_1, or their ratio to one another.

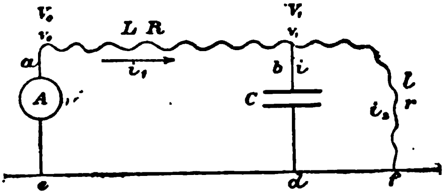

FIG. 12.

We have always, by the principle of continuity,

$$i_1 = i + i_2 \quad \ldots\ldots\ldots \quad (1);$$

also, at any instant

$$i = C\frac{d v_1}{d t} \quad \ldots\ldots\ldots \quad (2);$$

and by the usual current equation

$$l\frac{d i_2}{d t} + r i_2 = v_1 \quad \ldots\ldots\ldots \quad (3);$$

but we may write, as the currents are simply periodic,

$$i_1 = I_1 \sin p t \quad \ldots\ldots\ldots \quad (4);$$

where $p = 2\pi n$, *n* being the frequency of the periodic current in *a b*, and *t* the time reckoned from the instant when the current in this first section is zero.

By elimination of v_1, i_1, and i from the above four equations we find easily that

$$C\,l\,\frac{d^2 i_2}{d t^2}+C\,r\,\frac{d\,i_2}{d\,t}+i_2=I_1 \sin p\,t \quad . \quad . \quad . \quad (5).$$

Since i_2 must also be a simple periodic current, lagging in phase behind that of the current i_1, we may take i_2 to be of the form,

$$i_2=I_2 \sin (p\,t-\theta) \quad . \quad . \quad . \quad . \quad . \quad (6).$$

Hence by a differentiation of (6), and substitution in (5), we arrive at

$$(1-CLp^2)\,I_2 \sin (pt-\theta)+Crp^2\,I_2 \cos (pt-\theta)=I_1 \sin pt \ (7),$$

which, by a well-known transformation (see *Lemma*, § 17, Chap. III., Vol. I.), may be put in the form,

$$I_2 \sqrt{(1-C\,l\,p^2)^2+C^2\,r^2\,p^2} \sin (p\,t-\theta+\phi)=I_1 \sin p\,t \ \ (8).$$

Both sides of this equation (8) are expressions for the same thing—namely, the value of i_1—hence equating coefficients, we have,

$$\left(\frac{I_1}{I_2}\right)^2=(1-C\,l\,p^2)^2+C^2\,r^2\,p^2 \quad . \quad . \quad . \quad (9).$$

Putting $a=1-C\,l\,p^2$, and $b=C\,r\,p$, we have,

$$\left(\frac{I_1}{I_2}\right)^2=a_2+b_2 \quad . \quad . \quad . \quad . \quad . \quad (10).$$

This gives us the ratio of the maximum or square root of the mean square values, of the currents in the two sections of the line on either side of the condenser.

It is convenient next to shift the origin of the time, and take the instant when the current i_2 is zero as a point from which to reckon the time.

Doing this we can write,

$$i_2=I_2 \sin p\,t \quad . \quad . \quad . \quad . \quad . \quad (11),$$

and, accordingly, from (10),

$$i_1=I_2 \sqrt{a^2+b^2} \sin (p\,t+\theta)\,;$$

or $$i_1=I_2\,(a \sin p\,t+b \cos p\,t) \quad . \quad . \quad . \quad (12)\,;$$

hence, $$i_1-i_2=I_2\,(\overline{a-1} \sin p\,t+b \cos p\,t) \quad . \quad . \quad (13)\,;$$

but from (1) and (2)

$$i_1 - i_2 = C \frac{d v_1}{d t};$$

$$\therefore C \frac{d v_1}{d t} = I_2 (\overline{a-1} \sin p t + b \cos p t);$$

or

$$v_1 = \frac{I_2}{C p} (b \sin p t + \overline{1-a} \cos p t) \quad . \quad . \quad (14);$$

$$\therefore V_1 = \frac{I_2}{C p} \sqrt{\overline{a-1}^2 + b^2} = I_2 \sqrt{r_2 + p_2 l_2} \quad . \quad . \quad (15).$$

We have next to find the value of V_0. We see that

$$v_0 - v_1 = L \frac{d i_1}{d t} + R i_1 \quad . \quad . \quad . \quad . \quad (16);$$

and if we substitute in (16) the value of i_1 given in (12), and of v_1 given in (14), and integrate, we arrive at

$$v_0 = I_2 \left\{ \left(R a + \frac{b}{C p} - L p b\right) \sin p t + \left(R b + \frac{1-a}{C p} + L p a\right) \cos p t \right\};$$

but, since $\frac{b}{C p} = r$, and $\frac{1-a}{C p} = p l$, we get by proper substitution in the above equation, and by the application of the rule for harmonic maxima, the equation,

$$V_0 = \frac{I_2}{C p} \sqrt{(A^2 + B^2)(a^2 + b^2) + 2 B b - 2 A a + 1} \quad (17),$$

where

$$A = 1 - C L p^2; \qquad a = 1 C l p^2;$$

$$B = C R p; \qquad b = C r p.$$

Equations (15) and (17) give us the values of the maximum or mean potentials at the generator and condenser end of the line *a b*. If we divide equation (17) by equation (15), we get a value for the ratio of V_0 to V_1. A little tedious process of division and substitution brings us finally to the required result, which is,

$$\frac{V_0}{V_1} = \sqrt{(A^2+B^2) + (1 - 2 C l p^2) \frac{R^2 + p^2 L^2}{r^2 + p^2 l^2} + \frac{2 L l p^2}{r^2 + p^2 l^2} + \frac{2 R r}{r^2 + p^2 l^2}} \quad (18)$$

This last equation furnishes us with the required result, viz., the ratio of the maximum or mean potentials at the ends of the inductive line *a b* in terms of the coefficients of inductance, capacity, and resistance.

Given V_0, it enables us to calculate V_1, and to say whether V_1 is greater than, less than, or equal to V_0.

Let us examine some particular cases. Suppose $r^2+p^2l^2=\infty$ —that is, suppose the section of the line beyond the condenser removed—then

$$\frac{V_0}{V_1}=\sqrt{A^2+B^2}=\sqrt{(1-CLp^2)^2+C^2R^2p^2}. \quad . \quad (19).$$

This reduced case was treated by Dr. Hopkinson long ago,[*] and he showed, as we can easily see, that it is possible for the ratio of V_0 to V_1 to be *less* than unity—that is, for the potential at the receiving end, or at the condenser, to be *greater* than the potential at the sending end; for it is evident that for certain particular values of the quantities CLp^2 and $C^2R^2p^2$ the value of the quantity under the radicle in equation (19) may be a proper fraction. When this is the case its square root will also be a proper fraction, and hence V_1 will be greater than V_0.

Equation (19), giving us the ratio between the potential difference at the terminals of the alternator and the condenser, may be directly obtained by an analytical process of a simple character, instead of by a process of reduction from a mere general case of a shunted condenser. In considering the reduced case we may proceed thus:—As before, let V_0 and v_0 stand for the maximum and instantaneous values of the potential difference at the poles of the alternator; let V_1 and v_0 be the same quantities at the terminals of the condenser; and let I and *i* be the same for the current flowing into the condenser having a capacity C, whilst the line connecting the condenser with the alternator has an inductance L and a resistance R. We have then, by fundamental equations, the following relations:—

The value of the instantaneous potential difference v_1 at the terminals of the condenser is obtained from the instantaneous value of the current flowing into it by the relation

$$\frac{1}{C}\int idt=v_1 \quad . \quad . \quad . \quad . \quad . \quad (20).$$

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[*] See *Proceedings of the Institution of Electrical Engineers* for 1884, page 513.

Also, the value of the current i is given by the fundamental equation

$$L\frac{di}{dt}+Ri=v_0-v_1 \quad . \quad . \quad . \quad . \quad . \quad (21).$$

Hence we have

$$L\frac{di}{dt}+R_1+\frac{1}{C}\int i\,dt=v_1 \quad . \quad . \quad . \quad . \quad (22).$$

Consider i to be a sine function in form, so that

$$i=I\sin pt \quad . \quad . \quad . \quad . \quad . \quad (23).$$

Then by differentiation and substitution we have

$$LpI\cos pt+RI\sin pt-\frac{I}{Cp}\cos pt=v_0\,;$$

or

$$\left(Lp-\frac{1}{Cp}\right)I\cos pt+RI\sin pt=v_0 \quad . \quad (24)\,;$$

which by the usual transformation (see *Lemma*, § 17, Chap. III., Vol. I.), becomes

$$I\sqrt{\left(Lp-\frac{1}{Cp}\right)^2+R^2}\sin(pt-\theta)=v_0 \quad . \quad (25).$$

Hence the maximum value of v_0, viz., V_0, is given by the equation,

$$V_0=\frac{I}{Cp}\sqrt{(1-CLp^2)^2+C^2R^2p^2}. \quad . \quad . \quad (26).$$

But from equations (20) and (23), we have also, by substitution and integration, that $V_1=\frac{I}{Cp}$. Hence, by substitution of this last, in equation (26), we arrive at

$$V_0=V_1\sqrt{(1-CLp^2)^2+C^2R^2p^2} \quad . \quad . \quad (27),$$

which is equation (19) before obtained. On looking at this equation we see that the effect of inserting the condenser across the poles of the alternator is first algebraically equivalent to reducing the inductance of the whole circuit of the armature; and we may say that a condenser of capacity C, when traversed by periodic condenser currents of frequency n, acts in any circuit as equivalent to an impedance of magnitude $\frac{1}{Cp}$. It also acts as if it had a negative inductance equal to $\frac{1}{Cp^2}$, where p, as usual, stands for $2\pi n$. By a negative inductance $\frac{1}{Cp^2}$ must be understood a power of nullifying positive inductance in a conductor in series with the condenser numerically to the amount of $\frac{1}{Cp^2}$ henries. Suppose, then, that a condenser of capacity C is placed in series with an inductive resistance of inductance L and resistance R, and a periodic potential difference equal to V_0 permitted to act on the two in series. The resultant inductance of the whole circuit is $L-\frac{1}{Cp^2}$, and the resultant impedance is

$$\sqrt{R^2+\left(L-\frac{1}{Cp^2}\right)^2p^2}.$$

Hence the current through the condenser is equal to

$$\frac{V_0}{\sqrt{R^2+\left(L-\frac{1}{Cp^2}\right)^2p^2}}.$$

If the potential difference of the two sides of the condenser is called V_1, and the equivalent impedance of the condenser is $\frac{1}{Cp}$, we may consider that the value of V_1 is obtained by taking the product of this so-called impedance of the condenser, $\frac{1}{Cp}$, and the value of the current flowing through it. Hence we have,

$$V_1 = \frac{V^0}{\sqrt{R^2+\left(L-\frac{1}{Cp^2}\right)^2p^2}}\frac{1}{Cp};$$

but this is the same expression as that deduced before, in equation (27), for the ratio of V_1 and V_0. Thus the equation for the ratio of the pressures may be regarded as being built up on the assumption that a condenser behaves towards alternating currents as an impedance causing fall of potential in a current passing through it, and capable of nullifying inductance in a circuit connected in series with it; and such a view leads to an equation from which it is immediately seen that under some conditions V_1 must be greater than V_0.*

We may regard a condenser, when subjected to periodic currents, as a non-dissipative impedance, if the term may be allowed, having a negative self-induction. A condenser allows a flux of electricity to take place backwards and forwards through its dielectric, and, as far as alternating currents are concerned, it may be said to have a conductivity for electricity.

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* Mr. O. Heaviside points out (in a private letter) that, if a condenser has a true dielectric conductivity K, and a capacity, or permittance, as he calls it, C, then for simple periodic currents of frequency $n=p/2\pi$ the condenser acts as if it were a coil of resistance R′ and inductance L′, where

$$R'=\frac{K}{K^2+C^2p^2}, \text{ and } L'=\frac{-C}{K^2+C^2p^2}.$$

The reciprocal of the impedance of the condenser, which he calls the "admittance," is $(R'^2+p^2L'^2)^{-\frac{1}{2}}=(K^2+C^2p^2)^{\frac{1}{2}}$. Hence, for coils and condensers we have the following qualities, which are analogous :—

Coils *have*	Condensers *have*
Resistance R.	*Conductance* K.
Inductance L.	*Permittance* C.
Impedance $(R^2+p^2L^2)^{\frac{1}{2}}$.	*Admittance* $(K^2+p^2C^2)^{\frac{1}{2}}$.

For condensers having no sensible true conductance (perfect condensers) $K=0$, and the inductance becomes $-\frac{1}{Cp^2}$, and the impedance $\frac{1}{Cp}$, as stated in the text. These statements are obviously consequences deducible from the pair of fundamental differential equations for "inductive" and "permittive" circuits, viz. :—

$$L\frac{di}{dt}+Ri=v,$$

and

$$C\frac{dv}{dt}+Kv=i;$$

whence everything else is deduced. For further conceptions on resistance and conductance operators, the reader is referred to a Paper by Mr. Heaviside in the *Philosophical Magazine* for December, 1887. The term "impedance" has now become absorbed into practical science. If at any future time alternating currents of very high frequency become employed in electro-technical work, the capacity effects of circuits will make themselves more evident to the practical man, and then the quantity above called the "admittance" will be forced into view, and become a candidate for notice and for name. When working at very slow alternations, the *resistance* of the circuit is its most important quality. At higher alternations the *inductance* forces itself into view, and at higher still the *capacity* can by no means be ignored.

It is very easy to state the conditions under which this is the case. In order that V_1 shall be greater than V_0, or that there may be a rise of pressure, we must have

$$\sqrt{(1 - C L p^2)^2 + C^2 R^2 p^2}$$

less than unity: hence we must have

$$(1 - C L p^2)^2 + C^2 R^2 p^2 < 1,$$

or

$$1 + C^2 L^2 p^4 - 2 C L p^2 < 1 - C^2 R^2 p^2,$$

or

$$C < \frac{2 L}{R^2 + p^2 L^2} \quad . \quad . \quad . \quad . \quad . \quad (28).$$

If L, R, and p are constant, the value of C which makes the ratio of V_1 to V_0 a maximum is

$$C = \frac{L}{R^2 + p^2 L^2}.$$

Hence, if the capacity, C, of the condenser, measured in farads, is *less than* the quotient obtained by dividing twice the inductance of the line, L, measured in henries, by the square of the impedance $\sqrt{R^2 + p^2 L^2}$, we shall, under these circumstances, find a rise in pressure at the condenser end. For example, suppose the value of n or the frequency is 67, then $p = 421$, and $p^2 = 177{,}241$. If $R = 1$ ohm, and $L = \cdot 1$ henry, then $R^2 + p^2 L^2 = 1{,}773$, and there ought to be a rise in pressure if C is greater than 112 microfarads; or, if $R = 1$ ohm, and $L = 100$ henries, then $R^2 + p^2 L^2 = 1{,}772{,}410{,}000$, and there ought to be a rise in pressure if C is greater than one-eighth of a microfarad. Generally speaking, the greater L, the less will be the critical value of C. For high frequencies the criterion of rise of pressure at the condenser end is

$$C < \frac{2}{L p^2}.$$

That is to say, the critical capacity is just twice that which will at the given periodicity nullify the inductance of the armature circuit. It is worth while to note that even if the criterion for rise of pressure at the condenser end is fulfilled by L, R, C, and p, yet, as seen from equation (18), a sufficiently small impedance ($\sqrt{r^2 + p^2 l^2}$) in the shunt may nullify the effect and force V_1 to be less than V_0.

These *condenser effects*, as they may be called, are very strikingly shown when currents of high frequency are used. Quite recently, Mr. Nikola Tesla has published some interesting observations and experiments on alternating currents with the very high frequencies of 10,000 to 20,000 alternations per second,[*] and amongst these he has described an experiment with a condenser joined across the poles of such an alternator. A machine was used giving about 20,000 alternations per second. Two bare wires about 20 feet in length were attached to the poles, and their ends connected to the terminals of a condenser. The difference of potential between parallel points on these wires was explored by a voltmeter, and it was found that the potential difference of parallel points on the wires steadily rose inch by inch from 65 volts at the terminals of the alternator to 120 volts at the terminals of the condenser; and the writer states that observations on the self-induction of the armature in its position of maximum and minimum inductance showed that the capacity which gave the greatest rise at the condenser end correspond apparently to that which would about nullify the mean self-induction calculated from the observed maximum and minimum. This entirely corresponds to the above theoretical deduction.

The fact that when a condenser is thus charged by an alternating-current machine its terminal potential difference may be very much greater than that of the machine terminals, at similar speeds and excitation, but with the condenser removed, appears to have been noticed experimentally prior to the time when the simplest case was mathematically treated by Dr. Hopkinson. In the Paper of the latter above referred to, it is mentioned that Dr. Muirhead had observed it experimentally. In the discussion which followed Dr. Hopkinson's paper Mr. Blakesley dealt with the same matter in some geometrical diagrams, and Prof. Ayrton mentioned that in 1878 or 1879 Mr. Munro took out a patent for the use of condensers in combination with an alternate-current machine.

§ 9. Diagram of Electromotive Forces.—The problem just treated analytically may be solved by geometrical methods by employing the clock-diagrams of electromotive forces as used by Mr. Blakesley, Mr. Kapp, and the author in the first volume of this work.

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[*] See *Electrician*, March 6, 1891, p. 549.

In such diagrams we take lines drawn radially in different positions from a centre O to represent the maximum values and relative phases of various electromotive forces. If such a diagram of lines is considered to revolve round a common central point, the projection of these radial lines on any diameter or line drawn through that centre will represent the instantaneous values of these electromotive forces. We proceed to draw such diagrams for the case of a generator yielding a simple periodic electromotive force acting on circuits of various kinds.

It will be advantageous to consider, as a preliminary, the simpler cases first, in which the poles of the alternator are closed by (1), an inductive circuit having no capacity; (2), by a condenser with no self-induction in series with it; (3), by a condenser in series with an inductive line, and then to discuss the complete problem; (4), of a condenser shunted by an inductive shunt and in series with an inductive charging circuit.

We may refer the reader in this connection to a series of clear elementary papers by Mr. Kapp on this matter, published in *The Electrician*, Vol. XXVI., pp. 197 and 229. Mr. Kapp shows how electromotive force diagrams may be drawn for a great number of cases, starting from three simple rules:

(i.) That component of the impressed electromotive force required to overcome resistance is in synchronism or in step with the current as regards phase.

(ii.) That component of the impressed electromotive force required to overcome self-induction is a quarter of a period in *advance* of the current in phase.

(iii.) That component of the impressed electromotive force which is necessary to overcome the counter electromotive force of the condenser is a quarter of a period behind the current as regards phase.

To draw the clock-diagram of electromotive forces for the first case, take any line O R (*see* Fig. 13) to represent the maximum value of the *resultant electromotive force* in an inductive circuit L R, joining the poles of the alternator A. We shall suppose the alternator armature to have negligible self-induction and resistance in its armature. This resultant electromotive force is that which has elsewhere been called the *effective electromotive force* in the circuit; it is numerically equal to the product of the true resistance R of the inductive circuit and the current I (maximum value) flowing in it.

The resultant electromotive force R I, as represented by the line O R in the diagram, is the resultant of two other electromotive forces, viz., of the back or counter electromotive force of self-induction, which is numerically equal to L p I, and which is in phase 90deg. behind the resultant electromotive force, and the impressed electromotive force acting in the armature of the alternator, and which we shall represent by V_0 (maximum value). Hence, to represent V_0, draw a line O L from O and at right angles to O R, and numerically equal to the quantity LpI. From R draw R V parallel and equal to O L, and join O V. Then O V will represent in relative phase and magnitude the value of V_0 or the impressed electromotive force, which, acting in the armature circuit will send the current I through the inductive circuit of impedance $\sqrt{R^2 + L^2 p^2}$. For O R is the resultant of O V and O L, and the diagram shows us that the resultant electromotive force and therefore also the current *lags* in phase *behind* the impressed electromotive force.

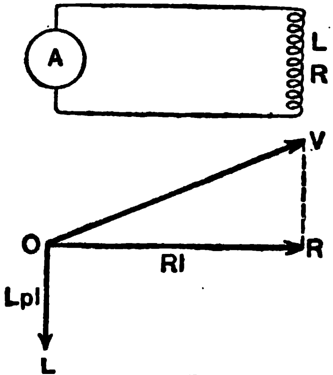

FIG. 13.

The second case, viz., the diagram of electromotive forces for a condenser in series with a non-inductive resistance, is constructed as follows:—Let O R (Fig. 14) as before represent the resultant electromotive force in the non-inductive circuit, that is, let O R be numerically equal to the product R I of the resistance R of the circuit and the current I flowing in it. The condenser exerts an electromotive force in the circuit, which must be represented by a line O C drawn in *advance* of O R and at right angles to it. It is obvious that this must be the case, because the potential difference of the plates of the condenser comes to a maximum one way or the other at the instant when the current flowing into or out of the condenser is zero; also when the current is beginning to flow into the condenser and just rising beyond zero the potential difference of the plates of the condenser is such as to assist the current flowing through the dielectric of the condenser. Hence the line O C, representing the electromotive force due to the condenser charge, must be drawn at right angles to O R and 90deg. in advance of it. Then draw from R a line R V parallel and equal to O C, and join O V. O V will represent V_0, or the impressed electromotive force of the alternator, by the harmonic variation of which the current I will be sent through

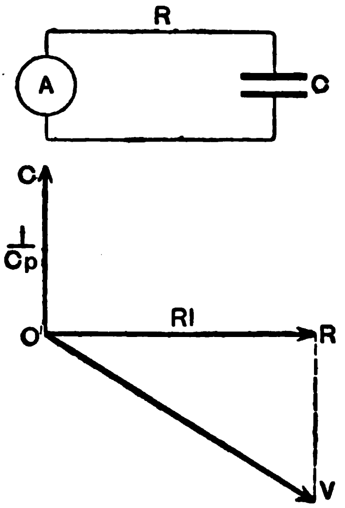

FIG. 14.

the condenser. We see that V_0 is in *advance* of the resultant electromotive force O R, and therefore of the current I, in phase.

The third case of the diagram of electromotive forces for the condenser in series with an inductive resistance is easily seen to be as follows:—Take O R (Fig. 15), as before, to represent the resultant electromotive force in the circuit; O R is numerically equal to the product of the ohmic resistance R of the circuit and the maximum current I flowing in it. Erect a line at O at right angles to O R, and set off O C 90deg. in *advance* of O R and representing the potential difference of the plates of the condenser, whose capacity is C, and O L in arrear of O R, representing the counter-electromotive force L p I in the inductive circuit. The magnitude of O C is obtained when we know the value of I.

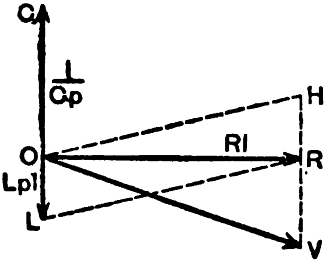

FIG. 15.

On a previous page we have shown from equations (20) and (23) (pages 377, 378), that the maximum value V_1 of the condenser plate potential difference is equal to $\frac{I}{Cp}$. Hence, O C must be made equal to $\frac{I}{Cp}$ on the same scale that O R is made equal to R I. We have then to find a line representing the maximum value of the impressed electromotive force V_0 in phase and magnitude, and such that R I is the resultant of V_0, LpI, and $\frac{I}{Cp}$. To obtain this line, draw R V parallel to C L and equal to O C—O L, that is, make R H equal to O L, and H V equal to

O C; join O V, and O V will represent in phase and magnitude the impressed electromotive force V_0, which will maintain the current I through the condenser.

Whether O V, that is V_0, will be in advance or in arrear as regards phase of the resultant electromotive force O R, and therefore of the current I, will depend on the relative magnitudes of O C or $\frac{I}{Cp}$ and O L or LpI. If O C = O L, then the impressed electromotive force will be in synchronism with the current, and this happens when $\frac{I}{Cp} = Lp$ or when $CLp^2 = 1$.

The diagram shows us at once that the impressed electromotive force $V_0 = OV$ of the dynamo may be less than equal to or greater than the pressure, $V_1 = OC$, at the terminals of the condenser; and that this is determined by whether the length of the line, $OV = \sqrt{OR^2 + VR^2}$, is greater or less than O C. We see that $VR = OC - OL = \frac{I}{Cp} - Lp1$, and hence that O V is equal to the square root of

$$\left\{R^2 + \left(\frac{1}{Cp} - Lp\right)^2\right\} I^2.$$

Hence the maximum value of the charging current, I, is given by the equation

$$I = \frac{CpV_0}{\sqrt{R^2C^2p^2 + (1 - CLp^2)^2}}.$$

Also, we have the same quantity given by the relation $I = CpV_1$; hence the ratio of V_0 to V_1 is given by the value of the quantity $\sqrt{(1 - CLp^2)^2 + C^2R^2p^2}$, as we have already seen. The clock-diagram has the advantage that it shows us at once the various lags, and gives explicitly to the eye a proof that a gradual increase in the value of the inductance, L, from zero upwards is accompanied by a progressive decrease in the value of the impressed electromotive force V_0, of the dynamo, as compared with the terminal pressure, V_1, at the condenser.

Also we can from the diagram determine the conditions under which the ratio of the potential difference V_1 at the terminals of the condenser to the impressed electromotive force of the alternator is a maximum. In other words find when the rise of pressure is a maximum, for if we refer to the diagram in Fig. 15 we see that

$$\frac{\mathrm{H\,V}}{\mathrm{O\,V}}=\frac{\sin \mathrm{HOV}}{\sin \mathrm{OHV}};$$

but since the angle O H V is independent of the value of the capacity C, this ratio is a maximum when the capacity of the condenser has such a value as to make the angle H O V a right angle. Hence H V, which represents the potential difference at

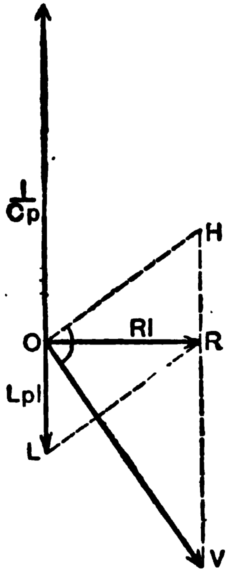

FIG. 16.

the terminals of the condenser, has its maximum ratio to O V, which represents the impressed electromotive force of the alternator, when the line O V is at right angles to O H. When this is the case the two triangles H O V, L O R (*see* Fig. 16) are both right angled, and similar triangles; therefore we must have

$$\frac{\mathrm{O\,L}}{\mathrm{L\,R}}=\frac{\mathrm{O\,H}}{\mathrm{H\,V}};$$

or
$$\frac{\mathrm{L}p}{\sqrt{\mathrm{R}^2+p^2\mathrm{L}^2}}=\frac{\sqrt{\mathrm{R}^2+p^2\mathrm{L}^2}}{\frac{\mathrm{I}}{\mathrm{C}p}};$$

or
$$\mathrm{C}=\frac{\mathrm{L}}{\mathrm{R}^2+p^2\mathrm{L}^2}.$$

This last line of reasoning brings us therefore to the same conclusion as that in equation (28) deduced by analytical reasoning.

We now pass on to consider, by the help of the foregoing, the general case of a condenser shunted by an inductive shunt. Let r and l be the resistance and inductance of the condenser shunt, and R and L that of the first section of the line, and let C be the condenser capacity. Take any line O R (*see* Fig. 17) to represent the product of the resistance R and the current flowing into the condenser I, that is, let O R represent R I. Draw O C at right angles to O R, and in magnitude equal to $\frac{\mathrm{I}}{\mathrm{C}p}$. Then O C represents the potential difference of the condenser plates. On O C describe a semicircle, and set off O B in such a direction that C B is to O B in the ratio of $p\,l$ to r. Then on the same scale on which O C represents the potential difference at the terminals of the condenser, that is, the impressed electromotive force in the shunt circuit, O B will represent the resultant or effective electromotive force, that is, it will represent the product $r\,\mathrm{I}_2$, and C B will represent $l\,p\,\mathrm{I}_2$. Again, divide O B in P so that O P is to O B as R is to r, then O P will represent in phase and magnitude $\mathrm{R}\,\mathrm{I}_2$. Hence we have O R representing R I, and O P representing $\mathrm{R}\,\mathrm{I}_2$. If we join P R, it is easy to see that this line must represent in phase and magnitude $\mathrm{R}\,\mathrm{I}_1$. For then the sides of the triangle O P R are proportional in magnitude respectively to I, I_1, and I_2, and at any instant the projections of these three sides on any line through O will represent the instantaneous values of i, i_1, and i_2, and the sum of any two of the projections will always be equal to the third. Hence the projections of I, I_1, and I_2 fulfil the conditions required by the principle of continuity, viz.: that the algebraic sum of the currents at any junction shall be zero; since there can be no accumulation of electricity.

If, then, we draw O A parallel and equal to P R, O A will represent in magnitude and phase the electromotive force $\mathrm{R}\,\mathrm{I}_1$, or the effective electromotive force in the main line. On O A describe a right-angled triangle O A L, such that O A is to A L as R is to Lp. Then O L represents the impressed electromotive force in the first section of the line. Join C L, and

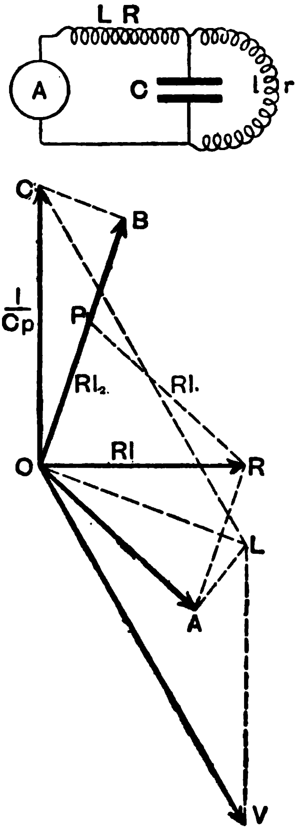

FIG. 17.

draw O V parallel and equal to C L, then O V represents the electromotive force of the alternator. For since the impressed electromotive force in the first section of the line is equal to the difference between the electromotive force of the alternator and the potential difference of the condenser plates, it must be represented by O L, where O L is the resultant of O V and O C. Hence, O V represents in phase and magnitude the maximum value V_0 of the electromotive force of the alternator on the same scale on which the line O C represents the maximum value of the potential difference $\frac{I}{Cp}$ or V_1 at the plates of the condenser, and on which O R, P R and O P represent R-times the value of the maximum values of the currents respectively into the condenser and those flowing in the first and second sections of the line.

Knowing that $OC = \frac{I}{Cp} = I_2 \sqrt{r^2 + p^2 l^2}$, and also seeing that the relation

$$I_1^2 = I_2^2 + I^2 - 2 I I_2 \frac{p l}{\sqrt{r^2 + p^2 l^2}},$$

is evident from the geometry of the figure, the student will have no difficulty in deducing from Fig. 17 also the equation (10) on page 375

$$\left(\frac{I_1}{I_2}\right)^2 = a^2 + b^2;$$

and also the equation (18) on page 376 for the ratio of V_0 to V_1. A careful examination of the diagram in Fig. 17 will show that under some conditions the current I_2 can be greater than the current I_1, that is, there can be an upward transformation of current, and also that O V can, under some conditions, be less than O C, or V_0 less than V_1. These and many other facts relating to the relative values of the currents in the main and shunt sections of the line, and the potential difference of the condenser plates as compared with the impressed electromotive force of the alternator, can be made out from the diagram, but must be left to the reader to discuss.

In his book on "Alternating Currents," p. 55 (2nd edition,) Mr. Blakesley has treated by his geometrical methods the case examined above, with the object of showing that the employment of a condenser in this manner in combination with a pair of inductive circuits may under certain conditions cause the current in the remote, or shunt, circuit to be greater than the current in the circuit in connection with the machine; and he shows there that a similar criterion to the one given above applies also to the relative current-strengths in the two sections—viz., that the current I_2 in section $b\,f$ will be greater than the current I_1 in section $a\,b$ if C is less than $\frac{2\,l}{r^2+p^2\,l^2}$.

In a later chapter we shall point out a practical application of the condenser to annul the disadvantages which an open magnetic circuit transformer possesses of taking a large magnetising current, based upon the power of a condenser to thus increase the current in one section of an inductive line.

Hence, taking the two separate cases of a simple condenser and a shunted condenser, we see that the maximum or mean potential V_1 at the terminals of the condenser will be less than, equal to, or greater than the maximum or mean potential at the terminals of the machine V_0, according as the capacity, C, of the condenser is greater than, equal to, or less than the quantity, $\frac{2\,L}{R^2+p^2\,L^2}$ in numerical value; and also that the maximum or average current-strength in the remote, or shunt, section of the line will be less than, equal to, or greater than the maximum or mean current-strength in the section of the line near to the machine, according as the capacity, C, of the condenser is greater than, equal to, or less than the quantity, $\frac{2\,l}{r^2+p^2\,l^2}$, in numerical value. Note that if R is measured in ohms and L in henries, C must be measured in farads.

Let us look again at the equation,

$$\left(\frac{V_0}{V_1}\right)^2=(1-C\,L\,p^2)+C^2\,R^2\,p^2,$$

and note what are the conditions under which V_1 will be *greater* than V_0, or the pressure at the condenser end greater than the pressure at the machine end of the line. We see that it depends upon whether the right-hand expression, when worked out numerically, is a proper fraction. Since almost any capacity which occurs in practice is numerically represented by a very small fraction when the farad is the unit, if p^2 is not very great $C^2\,R^2\,p$ will nearly always in practice be a proper fraction when we insert values of C and R in farads and ohms. Hence the condition of rise of pressure will depend almost always on whether $C\,L\,p^2$ is numerically greater than

2 when C and L are measured in farads and henries; and if C is very small, either L or p must be very large to secure this result, and *vice versa.* Hence, we are led to expect that if the inductance of the machine circuit is very large, a comparatively small capacity across its poles may give rise to a very great condenser effect; but if the inductance of the machine is small, a very large capacity will be needed to bring about the increased pressure at the terminals of the condenser.

The best way to see how the value of V_1, or the condenser potential, varies with variation of the capacity, other quantities being constant, is to plot the equation,

$$V_1 = \frac{V_0}{\sqrt{(1 - CLp^2)^2 + C^2R^2p^2}},$$

or—which comes to the same thing, and is simpler to plot—the equation,

$$y = \frac{1}{\sqrt{(1 - x)^2 + x^2}}.$$

This has been done in Fig. 18, and a curve representing the variation of V_1 in terms of C, or of the condenser plate potential difference in terms of its capacity, supposed variable, is there drawn, on the assumption that V_0, L, R, and p^2 have certain constant values. We see that the curve ordinate has a maximum corresponding to a certain capacity, and that beyond that point increase in capacity continuously diminishes the condenser plate potential difference.

The condenser effect will be at a maximum when C and L have such magnitudes that CLp^2 is unity, and C has at the same time a small value. In this case V_1 may be many times greater than V_0. In testing condensers with alternating-current machines, it is very important not to have that particular critical relation between C, p, and L, or the capacity, frequency, and inductance of the machine, which will bring about this *resonance* effect, or else the testing process may be a destructive process as far as the condenser is concerned.

We can also show that if the capacity of the condenser is fixed, there is a certain range of inductance of the circuit of the alternator within which the resonance effect takes place. For example, let $C = \cdot 1$ microfarad, as before, $p^2 = 273{,}947$, and

R = 10 ohms, then for the ratio of V_0^2 to V_1^2 we have the value,

$$\left(1-\frac{273{,}947\ L}{10^7}\right)^2+\frac{273{,}947\times 100}{10^8}=(1-{\cdot}027\ L)^2+{\cdot}27.$$

If L = 0, this ratio is greater than unity; if L = 74, the ratio is again greater than unity; but for values of L between 0 and 74, the ratio is less than unity. In other words, within these limits of the inductance the pressure at the poles of the condenser is raised.*

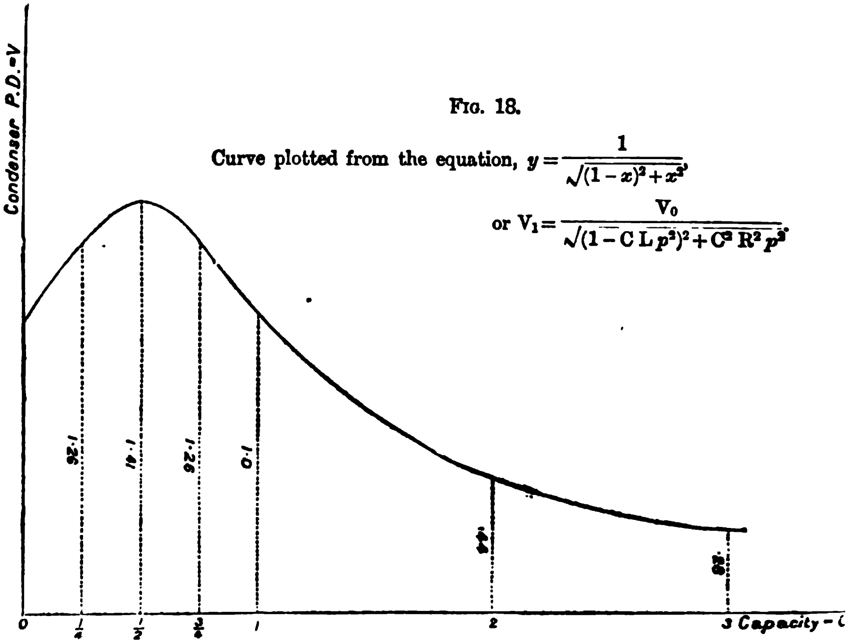

FIG. 18.

Curve plotted from the equation, $y=\dfrac{1}{\sqrt{(1-x)^2+x^2}}$,

or $V_1=\dfrac{V_0}{\sqrt{(1-C\,L\,p^2)^2+C^2\,R^2\,p^2}}$.

§ 10. **Practical Confirmation of the above Theory.**—The above theory is shown to be confirmed in its general character by the results of some highly interesting experiments made in April, 1890, at the works of Messrs. Siemens Bros. A Siemens W_1 alternator was kept running at a constant speed of 750 revolutions, and the exciting current was also kept constant. The current from this was sent into the thick-wire coil of a No. 2 Siemens transformer. The resistance of the primary circuit of this transformer was 0·115 ohm, and that of the secondary circuit 129 ohms. The terminals of the fine-wire circuit were connected to various lengths of single-conductor cable, having gutta-percha insulation and immersed in a tank; the cables being insulated at the far ends, and forming thus a condenser attached to the secondary of the transformer (*see* Fig. 19). The pressure was measured at the terminals of the machine, and at the terminals of the transformer on the secondary, or condenser, side. The experiments consisted in varying the length of the cable used so as to vary the capacity, and in observing the pressure at the two sides of the transformer whilst the dynamo was kept running at constant speed and excitation. The results are embodied in the following series of interesting curves. The horizontal distances in the diagrams represent the various capacities of the open-circuit cables or condenser attached to the terminals of the secondary of the transformer. The vertical ordinates in Fig. 20 represent the observed potential difference of the two surfaces of this condenser—that is, the potential difference at the secondary terminals of the transformer.

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* In applying these formulæ to the case of transformers connected with condensers it is necessary to point out to the reader that the R and L here used are not the steady current values of these quantities, but their values as affected by the mutual inductance of the two coils of the transformer.

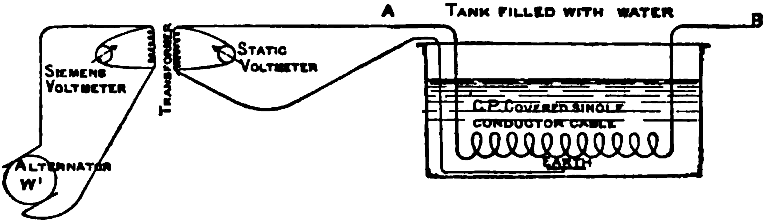

FIG. 19.—The Arrangement of Alternator, Transformer, and Cable in the Experiments on Condenser Effects made at Messrs. Siemens' Works, April, 1890.

It will be seen from Fig. 20 that when the capacity is zero this potential difference was 2,500 volts. As the length of cable was increased continuously, this potential difference rose up to 8,500 volts, corresponding to a capacity of ·2 microfarad, and then fell again to 2,500 volts, at a capacity of ·45 microfarad. Hence corresponding to a certain capacity—viz., ·2 microfarad—the pressure is multiplied about 3½ times, and there is a certain narrow range of capacity over which this exaltation of pressure takes place. At and beyond ·45 microfarad capacity, the presence of the condenser reduces the normal pressure continuously. The pressure on the primary side of the transformer is also increased, as shown in the curve given in Fig. 21, which represents a series of similar pressure observations taken on the primary side of the transformer. It will be seen that the same general effect takes place on the primary side. It will also be seen how well these curves deduced from observation agree as regards general form with the

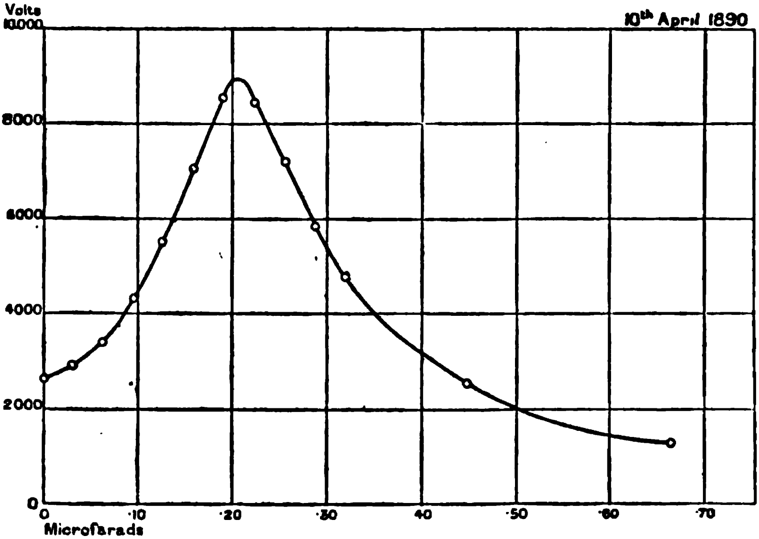

Fig. 20.—Curves showing the Variation in Voltage in the Secondary (high voltage) Circuit of a Transformer by Varying the Capacity in the Secondary (high voltage) Circuit. The experiments were made with a No. 2 Siemens transformer, and current was obtained from a W^1 Siemens machine, frequency being 100 ∿. The exciting current was kept constant, and the alternator was kept running at 750 revolutions during all the experiments.

theory as illustrated by the curve in Fig. 18. The curves in Figs. 20 and 21 are generally similar, but, if superimposed, will be found to be not quite so. If the ratio of corresponding ordinates is set off so as to form a fresh curve (Fig. 22), this curve will give the variation of change ratio of the transformer corresponding to the various capacities, and we see that this change ratio is altered progressively from 1:43 to 1:57, as the capacity of the condenser on the secondary is changed from zero to ·65 microfarad. It is evident, therefore, that in applying transformers to test cable, such as concentric cable, which possesses sensible capacity, we must be on our guard against

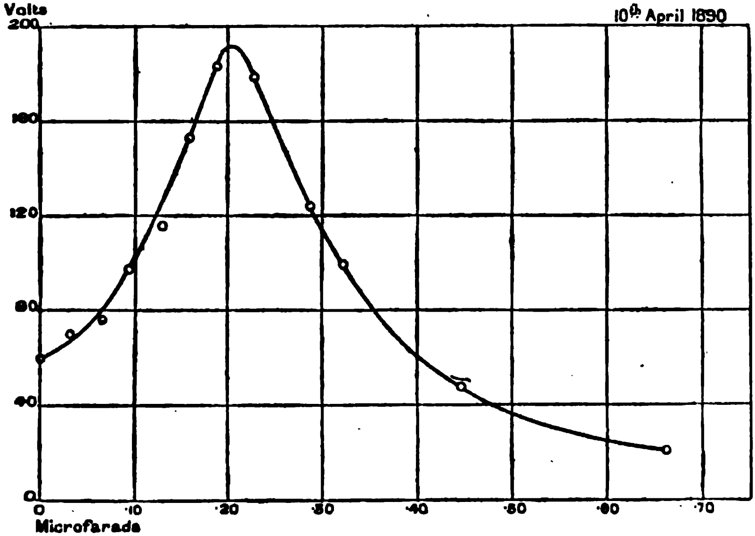

FIG. 21.—Curves showing the Variation in Voltage in the Primary (low voltage) Circuit of the same Transformer by Varying the Capacity in the Secondary (high voltage) Circuit. The experiments were made with a No. 2 transformer, and current was obtained from a W^1 Siemens machine, the frequency being 100 ∿. The exciting current was kept constant, and the alternator was kept running at 750 revolutions during all the experiments.*

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* The reader is advised to compare these curves in Figs. 20 and 21 with the curves in Figs. 28 and 29 of § 11, Chap. V., Vol. I., in which a similar effect of rise of pressure produced by a critical capacity in some of Dr. Hertz's experiments is shown.

this alteration of the change ratio of the transformer, or else we may be misled as to the real pressure being applied to the cable.

These considerations point out that in applying either transformers or alternators to circuits which have capacity, we must have regard to the fact that for certain critical values of the inductance and the capacity for given frequencies, there may be a very considerable increase in the potential difference of the two sides of the condenser over and above that of the poles of the alternator or transformer when no condenser is present. Such effects have often been noticed in practice. It has been frequently found that if a transformer which gives on its open secondary circuit a certain potential difference is applied to test the insulation of a length of concentric cable by connecting its terminals to the two conductors, the far ends of the cable be insulated, under some circumstances an increased potential difference is observed between the free ends of the cable over and above that at the terminals of the transformer when the cable is not connected to it. When transformers have been employed to test the insulation of armatures of high-pressure alternators, it has been noticed that under some circumstances

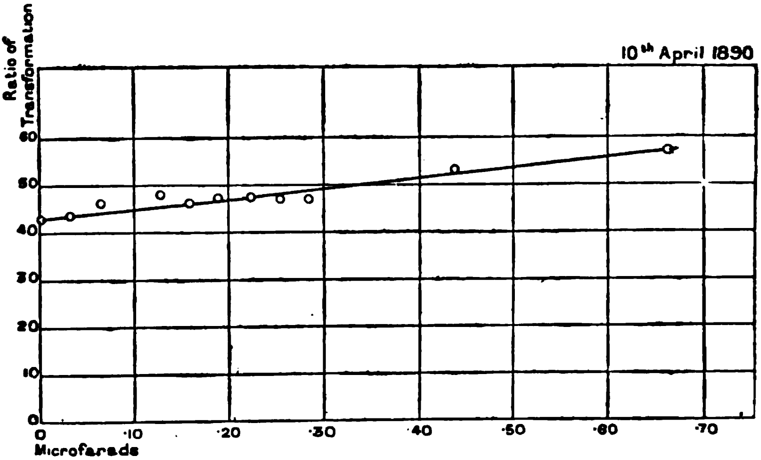

FIG. 22.—Curves showing the Dependence of the Ratio of Transformation of Pressure from Primary to Secondary Circuit on Capacity of Secondary resulting from Figs. 4 and 5.

large snapping sparks will jump off over air distances which could not possibly permit discharges at the actual potential difference of the secondary terminals of the transformer so used when unconnected with any such body having capacity.

In employing an alternator or transformer to test insulation between two opposed conductors, or in any way in which the opposed terminals gain capacity, it is necessary to be on the watch for this possible rise of pressure, and not to infer, because a transformer gives, say, 2,000 volts on open circuit between its poles when measured with an electrostatic voltmeter, that therefore this is the measure of the pressure which is being applied to a dielectric which forms the insulator of a condenser joined in across the poles of that transformer.

It is possible that under some circumstances errors may be committed in the mere use of an electrostatic voltmeter to measure potential difference between the poles of an alternator or a transformer, if that voltmeter happens to possess a certain capacity in relation to the inductance of the circuit in which it is joined in parallel.

The general fact which must be emphasised is then that when a condenser such as is formed by a suitable length of concentric cable has its opposed surfaces connected to the two poles of a transformer or of an alternator having a certain inductance in its armature in relation to the capacity of the condenser and the frequency of the current, the potential difference of the two surfaces of this condenser is more or less increased above the value of the potential difference of the poles of the alternator or transformer if the condenser is not there. This *condenser effect* may be of such a degree as to multiply by many times the normal potential difference of the poles of the generator. If the condenser is formed of a length of concentric cable, this cable acts in all as one single condenser. If the concentric cable is open-circuited at the far end the potential difference of the cable conductors is everywhere the same and equally raised. If there is a current flowing through the cable then there will be the usual fall of volts along the cable, but the potential difference of the cable conductors at the dynamo end will be greater than would be the dynamo terminals if the cable were absent. Whenever considerable lengths of concentric cable are connected to transformers or to an alternator of sufficient armature self-induction, this *rise of pressure* or *condenser effect* will generally make itself felt, and can only be annulled by taking a sufficiently great current through the cable. Hence when distribution systems are arranged in which at the generating end of the trunk lines, step-up transformers raise the pressure of low-pressure alternators and deliver the current into concentric cables, more or less troublesome effects of this nature may make themselves apparent when such cables are switched on or off the step-up transformers, or are increased or decreased in number in parallel.

The condenser effect we have been considering, and in particular the alteration of the change-ratio of a transformer which takes place when its secondary circuit is connected to a conductor system having a certain capacity in relation to the inductance of that secondary circuit, is found to operate in many curious ways in the practical use of such combinations. For instance, if a pair of alternators separately excited are working in parallel on an omnibus main leading to a conductor system of no sensible capacity, then it is well known that if the dynamos are synchronised, and contributing equally to the outgoing current, the method adopted to take one dynamo out of circuit would be to lower its exciting current, and when its outgoing current fell to zero to sever its connection with the omnibus main. If, however, the alternators are working through step-up transformers, and into a conductor system consisting of concentric cable, it is found by experience that the exciting current of the dynamo to be taken out must be raised, and not lowered, in order to bring it into a condition in which it can be cut off from the omnibus main without dangerous sparking at the switch; and, conversely, in putting it into parallel the incoming alternator has to be excited to a lower electromotive force than is necessary to maintain the standard potential difference at the terminals of the step-up transformer before putting it into connection with the omnibus main. This is obviously due to the fact that the pressure at the secondary terminals of the step-up transformer is altered by the very act of putting it into connection with the conductor system, and hence the excitation of the alternator at the moment of making or breaking connection with the main must be such as will bring the potential difference of the free secondary terminals of the step-up transformer to a value equal to the potential difference of the two points on the conductor having capacity to which they are about to be connected, or from which they have just been severed; and when the connection of the alternator is made, the excitation can be altered to divide the load on the machines properly. This would not be the case if high-tension alternators of very small inductance were set to work in parallel on such a concentric conductor system. In this case the condenser effect is practically nothing, and the behaviour of the machines in going into or out of parallel would present nothing unusual.

§ 11. Rise of Pressure Effects in the Case of the Ferranti Trunk Mains.—Remarkable practical illustration of the above described effects presented itself during the laying and working of the Ferranti Tubular Trunk Mains in London. These effects, at the time, were much misunderstood, and gave rise to considerable discussion.* It was found, when the full length of cable from Deptford to the sub-station in London, a distance of nearly six miles, was connected to transformers which raised the pressure of alternators from 2,400 to about 10,000 volts, that the following effects presented themselves:—

(i.) There was a considerable flow of current into the cable when the London end was insulated, and this flow increased with the length of the cable employed. This current is the *condenser current* of the cable, or the flux of current which takes place across the dielectric of the cable. It is proportional in magnitude to the length of cable used, to the speed of the machine, and to the voltage at the dynamo end, and is normally at about the rate of 1·2 or 1·3 amperes per mile run. Hence, when a double loop of the cable of 11·5 miles in length from Deptford to London and back was employed, it was found that the condenser current at 10,000 volts was about 12 to 14 amperes.

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* Discussions on the subject of this effect, rather misnamed the "Ferranti effect," occurred at the Physical Society of London during the discussion on a Paper by Mr. Swinburne on "Alternate-Current Condensers," and was continued by Mr. Swinburne, Mr. Glazebrook, Professor Ayrton, and Mr. Kapp, in various articles and papers, for which the reader is referred to *The Electrician*, Vol. XXVI., Dec. 19th, 1890, p. 214; Dec. 26th, p. 232; Jan. 2nd, 1891, p. 260. Mr. Gisbert Kapp wrote an article on "Capacity and Self-Induction in Alternate-Current Working," published in *The Electrician* for Dec. 19th, 1890, p. 197, and Dec. 26th, p. 229, in which condenser effects are discussed with his usual clearness and care. This matter was also discussed by the author in a Paper read before the Institution of Electrical Engineers of London, on May 7th, 1891. See *Journal of the Institute of Electrical Engineers*, Vol. XX., p. 362, 1891, "On Some Effects of Alternating-Current Flow in Circuits having Capacity and Self-Induction."

(ii.) When the 1,250 horse-power alternator was excited and driven at a certain speed, and the insulated cable together with a step-up transformer at the generating end switched on to the machine, it was found that the pressure at the terminals of the machine was increased, and the step-up ratio of the transformer was also increased in such fashion that the 1 : 4 step-up ratio of the transformer used was increased by about 15 to 20 per cent. Hence the pressure measured anywhere along the cable was found to be greater than four times the pressure at the dynamo terminals.

(iii.) When the cable was insulated at the far end the potential difference between the inner and outer copper was found to be everywhere the same, and everywhere equally raised. There was found to be no progressive rise of pressure along the cable from the home to the far end.

(iv.) When the cable was connected directly and without the interposition of the step-up transformer to the larger alternators excited so as to give directly 10,000 volts, then no sensible increase of terminal pressure was found upon switching on a length of the insulated cable. These alternators, as before described, have very small armature resistance and inductance. A series of experiments was made on January 9th, 1891, to examine more fully these effects. The arrangement of dynamo and cables was as shown in Fig. 23. One of the 1,250 horse-power dynamos was set apart for the purpose, and excited so as to supply current at about 2,500 volts or so. The current from this dynamo was led through the primaries of two 150 horse-power transformers joined in parallel, and which raised the pressure from 2,500 to 10,000 volts. At this pressure a current from the secondaries was sent into the concentric cable at Deptford, thence to the sub-station in Trafalgar-square in London by one main, and back to Deptford on the other trunk main. This total distance is 20,224 yards, or 11·49 statute miles.

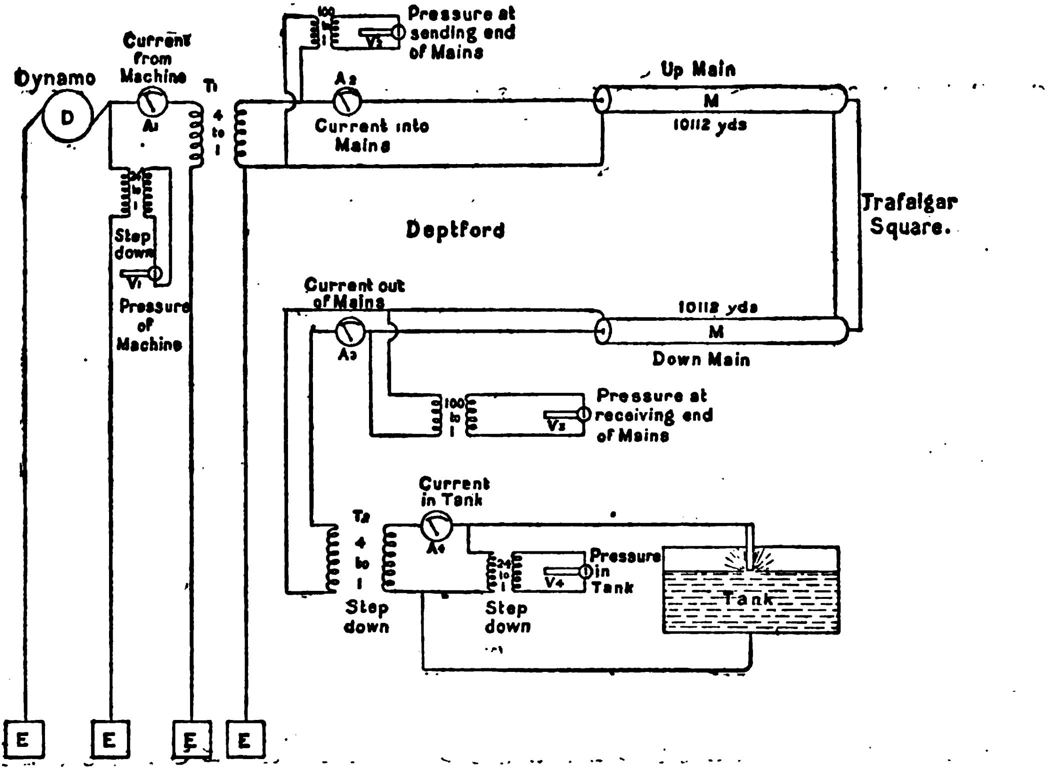

FIG. 23.—Diagram of Connections in Experiments on Pressure Distribution in Ferranti Trunk Mains.—V_1, V_2, V_3, V_4, Voltmeters. A_1, A_2 A_3, A_4, Ammeters. D, Dynamo., T_1, 150 H.P. Step-up Transformers. T_2, 150 H.P. Step-down Transformers. M, Trunk Mains. Tank, Large Water Tank into which a copper bar carrying the current was lowered to take up energy. E, Earth Plates.

Arriving back at Deptford, the current was again reduced from 10,000 to 2,500 volts, and the energy taken up in water resistance in a water tank at the latter pressure. The pressure at different parts of the system was measured by Cardew voltmeters, the high pressures being reduced by 100 : 1 pilot transformers. The currents were measured by Evershed ammeters. The current and pressure were measured at four places—viz., at the terminals of the dynamo, at the beginning, or entrance, of the trunk main, at the end of the trunk main, and, after reduction, at the tank. Observers stationed at these different instruments took simultaneous observations at a signal given by the sound of a whistle, and in this way the simultaneous values of the pressure and current were obtained at these four places. The transformers used for raising and lowering the pressure were the 150-horse-power size, having on the primary side 1,120 turns of wire, of resistance 3·5 ohms, and on the secondary side 280 turns of wire, having a resistance of ·2442 ohm. Hence these transformers were 4 : 1 transformers. There were, in addition, a pair of pilot transformers, which had a change ratio of 100 : 1, and which reduced from 10,000 to 100 volts for voltmeter purposes. The observations consisted in exciting the dynamo to various voltages, and observing the current and pressure at the four places named, whilst different loads were placed on the system by taking up more or less current in the tank.

Under these circumstances it was found that when the transformers at the far end were not loaded at all, the current going into the cable at the dynamo end under a pressure of about 10,000 volts was about 12 amperes. This is the *Condenser Current* of the mains. On loading up the transformers at the far end the current going into the cable at the dynamo end is also increased, but it is always greater than the current coming out of the cable. This last may be called the *Work Current*, and the former the *Resultant Current*. The work current is practically in quadrature with the condenser current, and is 90 deg. in phase in arrear of it. Hence the square root of the difference of the squares of the ingoing and outcoming currents of the cable gives the value of the condenser current. If this condenser current in amperes called I, and the mean potential difference in volts of the two surfaces of the condenser, or of the inner and outer tubular conductors of the tube, called V, and 2π times the frequency as usual denoted by p, then the capacity of the cable C in microfarads is related to I and V, so that

$$C = \frac{I}{pV} \times 10^6.$$

In the experiments referred to, the value of p was about 400, and the capacity calculated from the condenser currents of the cable at different loads was found to be from 3·5 to 3·8 microfarads for the whole 11·5 miles. Experiments made with a ballistic galvanometer and steady electromotive forces of 18 volts or so, showed that the capacity was nearly four microfarads. These experiments, therefore, showed that the condenser current was not very different from 12 or 14 amperes. Hence, the dynamo had to contribute 48 to 50 amperes to supply this condenser current through the 1 : 4 step-up transformers.

When the transformers at the far end were fully loaded it was found that there was a fall of potential down the trunk main, and that in proportion as the load increased the actual numerical difference between the ampere values of the currents going into and coming out of the cable was diminished, but still the square root of the difference of the squares remained about equal to 12 or 14, viz., the value of the condenser current of the cable.

The measurements of potential at the dynamo terminals and on the trunk main side of the 1:4 step-up transformers showed that the change-ratio of these transformers was affected by the capacity of the mains. The pressure at the dynamo end of the trunk main was always more than four times the pressure at the dynamo terminals. The increase was about 5 per cent. at full load, and 10 to 15 per cent. when all load was removed from the system. Hence not only is the pressure at the dynamo terminals raised by connecting these to step-up transformers joined to mains having capacity, but the step-up ratio of the transformers is also increased, the exciting current and speed remaining constant. These two effects are quite distinct from one another, and are due to different actions. The alteration of the change-ratio of the transformers is due to their construction, whilst the rise of pressure generally is due to the reaction of the condenser upon the self- induction of the armature circuit.

§ 12. **Further Discussion of Capacity Effects.**—Additional experiments made with one of the 625 horse-power Ferranti dynamos at Deptford have shown in a remarkably clear manner the way in which the *condenser effect* of the trunk mains renders itself evident in affecting the change-ratio of the step-up transformers and in altering the exciting current necessary to produce a given potential difference at the dynamo ends of the trunk mains. A preliminary experiment was made with the trunk mains disconnected, and the 4 to 1 step-up transformers alone attached to the dynamo. The exciting current was varied and the engine speed kept constant. The volts at both terminals of the transformers were measured by Cardew voltmeters connected through reducing 24 to 1 and 100 to 1 transformers. In this case no sensible capacity existed at all in connection with the system. The volts on the low-pressure (L.T.) side of the transformer will be called the *dynamo volts*, and the volts on the high-tension (H.T.) side will be called the *switchboard volts.*

The results of varying the exciting current and keeping the speed constant are shown in the following table :—

Experiment I.

Pressure Measurements with Dynamo attached only to Step-up Transformers. Circuit Open. No Mains Connected.

Revolutions of engine per minute.	Exciting current of dynamo in amperes.	Dynamo volts on L. T. side of transformer.	Switchboard volts on H. T. side of transformer.	Change-ratio of transformer.
52	98	2,633	10,650	4·04
52	82	2,345	9,400	4·05
52	72	2,105	8,450	4·01
52	65	1,961	7,800	4·03
52	55	1,661	6,700	4·03

Hence we see that the change-ratio of the transformer remains constant for variations of the pressure on its terminals, there being no load on the transformer. The dynamo and switchboard volts increase with the exciting current, but preserve the same ratio to each other. If, however, the four Ferranti trunk mains are successively connected to the omnibus bar, these mains being open-circuited at the London end, and acting only as condensers, then it is found that the dynamo volts and switchboard volts are both changed, and the ratio of them is changed also. The following table shows the nature of these changes.

Experiment II.

Pressure Measurements with Trunk Mains attached to Step-up Transformer on High-Tension Side. Circuits Open.

Revolutions of engine.	Exciting current in amperes of dynamo.	Dynamo volts on L. T. side of transformer.	Switchboard volts on H. T. side of transformer.	Change-ratio of transformer.	Number of trunk mains attached.
52	62	1,875	7,500	4·0	0
52	62	2,012	8,150	4·05	1
52	62	2,153	9,050	4·2	2
52	62	2,421 (?)	9,900	4·1 (?)	3
52	62	2,489	10,850	4·4	4

The above experiments showed clearly that when mains having capacity are connected to the high-tension side of the transformer, the pressure is raised on both sides even when the exciting current and dynamo speed remain quite constant. Also that the change-ratio of the transformer is altered. In the above case each of the mains added represented about 2 microfarads in capacity. Although the trunk mains were open-circuited at the London end, nevertheless a current was found to be passing into them, and this current was respectively, 8, 20, 31, and 44 amperes in all, when there were 1, 2, 3, and 4 trunk mains joined on to the step-up transformer. The frequency in this case was 83 per second.

The entire agreement of these observations with the theory given in § 8 was shown by comparing the above measured values of the *condenser currents* flowing into the four mains with the results obtained by calculation from the formula

$$I = C p V \times 10^{-6},$$

which gives us the condenser current in terms of the capacity, the mean potential difference of the inner and outer conductors and p or 2π times the frequency. In the above observations the value of p was $522 = 2\pi \times 83$. If we employ the above formula to calculate the capacity of the mains we can compare this value with the capacity directly measured by comparison with a standard condenser. Taking the results from Experiment II. above we tabulate the calculations as follows:—

Calculation of the Capacity of Ferranti Trunk Mains from the observed Condenser Currents at Various Voltages.

Mean potential difference of inner and outer conductors in volts.	Observed condenser current, in amperes, going into mains.	Total capacity of mains, calculated from formula $C = \frac{I}{pV} \times 10^6$ in microfarads.	No. of trunk mains connected.
8,150	8	1·9	1
9,050	20	4·2	2
9,900	31	6·0	3
10,850	44	7·7	4

Two of the trunk mains, of which there are four altogether, have each a total length of 6·60 statute miles, and two have each a length of 5·81 statute miles, depending on the position of the sub-station to which they run (see § 38.) Hence, the total length of trunk mains is 24·8 statute miles.

Since the above table shows that the total calculated value of the four mains together is 7·7 microfarads for 24·8 miles, it follows that the mean capacity is at the rate of ·31 microfarads per mile.

A careful measurement, by means of a standard condenser and ballistic galvanometer, was made of the capacity of two lengths of the mains. The capacity of two lengths of 11,114 yards, or 6·31 statute miles, showed the capacity between inner and outer conductor to be respectively 1·98 and 2·02 microfarads, or at the rate of ·313 and ·319 microfarads per mile. This agrees closely with the above calculated result, and it shows that the *condenser current* can be calculated with great accuracy by the formula $I = CpV$. On comparing the tables of Experiments I. and II., we see that the addition of the capacity of the cables to the secondary or high-pressure side of the step-up transformers does two things. 1st, it decreases the exciting current required to maintain a given voltage at the high-tension side of the transformers, or conversely for a given exciting current it raises the voltage. Thus for an exciting current of 65 amperes the dynamo volts are 1,961, and the switchboard volts 7,800, and the transformer change-ratio is 4·03 to 1. If, however, four trunk mains are connected to the system, adding a capacity of 7·7 microfarads to the secondary side, then 62 amperes of exciting current produce 2,489 volts at the dynamo terminals and 10,850 at the switchboard, and raises the change-ratio of the transformer to 4·4 to 1. Hence the dynamo terminal volts are increased 25 per cent. and the change-ratio of the transformer 10 per cent. by the addition of the 7·7 microfarads of capacity to the high-tension side of the step-up transformer. In seeking for a full explanation of these effects an examination of them shows that there are possibly two different classes of actions concerned. One of these actions is a result of combined inductance and capacity in the circuit, and the other, which has been particularly supported by Mr. Swinburne, is considered to be due to a re-action of the armature current upon the field magnets of the dynamo. The nature of the first-named action has been already discussed, but may be considered a little more in detail as follows:—Suppose a circuit having inductance L (*see* Fig. 24) to terminate on a condenser of capacity C, and let an impressed periodic electromotive force cause a current to flow in the inductive circuit completed by an earth return. If at any instant a current of strength i exists in the circuit, then its kinetic energy is $\frac{1}{2} L i^2$. If this current be left to itself by the withdrawal of the electromotive force it must expend this energy in charging the condenser up to a certain maximum

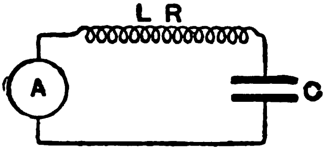

FIG. 24.

potential, say V; and the potential energy of the charge so given to the condenser is represented by $\frac{1}{2} C V^2$, this potential energy, $\frac{1}{2} C V^2$, being equal to the kinetic energy, $\frac{1}{2} L i^2$, which has disappeared in producing it. Hence for a given amount of kinetic energy the potential to which the condenser plate rises will be greater in proportion as the capacity C is less. On the other hand, the maximum current which is capable of being produced in the circuit depends upon the capacity of the condenser. If this capacity is zero, then the current and hence the kinetic energy capable of being produced by any electromotive force is zero, and hence also the potential to which the plate of the condenser will rise will only be equal to the potential produced by the alternator or source of electromotive force applied to the inductive circuit. On the other hand, if the capacity is very large, then although a large kinetic energy may be accumulated in the current flowing into it, yet it will, on account of this very great capacity, only raise the potential of the condenser slightly when converted into its equivalent in static charge or potential energy. Hence such a system, consisting of inductance and capacity in series, constitutes a path in which electricity when set in motion by momentary impressed electromotive force oscillates backwards and forwards, the energy being alternately kinetic and potential, but being continually frittered away by the ohmic resistance of the inductive circuit into heat.

This is a very familiar fact to those who have experience of long electric lighting circuits, either for arc lighting by continuous currents or for incandescent lighting by alternating currents. If the continuous current in a long underground insulated arc light circuit is suddenly switched off the insulation is very apt to break down, and will certainly do so unless in very good condition. The difficulties that have been met with in maintaining the insulation of such circuits is largely due to this cause. The proper method is to short-circuit the series dynamo, as is done in the case of the Thomson-Houston arc-light dynamos, and not to switch off suddenly a large circuit flowing in a long looped and therefore inductive circuit. Again, in the case of alternating currents, it has been found that if the pressure is suddenly switched on to or off from open circuits, having inductance and capacity, that the pressure rises at the far end to an injurious degree, and that the insulation is often injured thereby. It must be borne in mind in dealing with long insulated circuits supplied with alternating pressure that although the circuit may be "open" at the end remote from the dynamo, yet if the circuit possesses sensible capacity an alternating current will flow into it, and if its inductance exceeds a certain amount a phenomenon of increased pressure will present itself, due to the conversion of kinetic energy of the current flow into static pressure or potential energy in each period or cycle.

A little consideration will show that when certain relations between the capacity and inductance of the circuit are fulfilled that the mean or maximum pressure at the terminals of the condenser can become greater than the mean or maximum value of the impressed electromotive force. This has been rigidly demonstrated in a former paragraph. The equation there given—viz.,

$$L\frac{di}{dt}+Ri=v_0-v_1,$$

as the current equation applicable to the case of an impressed electromotive force acting upon a circuit having capacity and self-induction, can, by multiplication by $i\,dt$, be written

$$Li\frac{di}{dt}dt+Ri^2\,dt+v_1\,i\,dt=v_0\,i\,dt.$$

This is an equation of energy, and expresses in mathematical language the fact that the work expended on the circuit in any time dt by the impressed electromotive force v_0, and which is represented by the term $v_0\,i\,dt$, is used up in doing three things:—

(i.) In increasing the charge of the condenser, and which is represented by the term $v_1\,i\,dt$. For the current i flowing into the condenser is at any instant equal to $\frac{dq}{dt}$, the rate of increase of the charge of the condenser, and therefore

$$v_1\,i\,dt=v_1\frac{dq}{dt}dt=v_1\,dq,$$

or is equal to the product of the potential and increment of charge of the condenser, or to the element of work done in the time $d\,t$.

(ii.) The work supplied is used up partly in a dissipation of energy into heat by the ohmic resistance of the circuit, and the amount so dissipated in the time $d\,t$ is represented by $R\,i^2\,d\,t$.

(iii.) The energy supplied is used up partly in increasing the electro-kinetic momentum of the circuit, and this is represented by $L\,i\,\frac{d\,i}{d\,t}\,d\,t$, for this represents the increase in the value of the quantity $\frac{1}{2}\,L\,i^2$, which takes place in an element of time $d\,t$. Hence we have an equality at any instant between the rate of supply of energy and the rate at which it is being transformed into kinetic or potential forms, according to the equation

$$v_0\,i\,d\,t \quad = \quad v_1\,i\,d\,t \quad + \quad R\,i^2\,d\,t \quad + \quad L\,i\,\frac{d\,i}{d\,t}\,d\,t.$$

$$\left.\begin{array}{c}\text{Work done}\\ \text{on circuit}\\ \text{by im-}\\ \text{pressed}\\ \text{E.M.F. in}\\ \text{time } d\,t\end{array}\right\} = \left\{\begin{array}{c}\text{Increase of}\\ \text{potential}\\ \text{energy stored}\\ \text{in the con-}\\ \text{denser in}\\ \text{time } d\,t\end{array}\right\} + \left\{\begin{array}{c}\text{Energy dis-}\\ \text{sipated in}\\ \text{the circuit}\\ \text{in form of}\\ \text{heat in the}\\ \text{time } d\,t\end{array}\right\} + \left\{\begin{array}{c}\text{Work done}\\ \text{in increasing}\\ \text{the kinetic}\\ \text{energy of the}\\ \text{circuit in}\\ \text{the time } d\,t.\end{array}\right.$$

It has been shown that a solution of this equation tends to the result that V_1, or the maximum value of the potential difference of the terminals of the condenser, may for certain values of C, R, L and p become greater than V_0, the maximum value of the impressed electromotive force acting on the circuit. The circumstances under which this can take place are given by the diagram in Fig. 16.

Suppose that an alternator having an armature possessing self-induction has its terminals closed by a condenser, or has them connected to a pair of mains which have capacity relatively to one another, then the potential difference between these mains may become greater than that of the poles of the alternator if the main is removed, but still retaining the same speed and excitation. This is what the Deptford experiments described show to have been the case, and they show that the exciting current at a given speed, which is a measure then of the impressed electromotive force, must be diminished in proportion as the cable capacity is increased if the potential difference of the terminals of the condenser is to be kept constant. The view above taken that this increase of pressure is due to the combined action of the electro-magnetic momentum of the armature circuit, and to the capacity of the condenser which completes that circuit, has been considered by some writers as not conveying a full explanation of the matter. Mr. Swinburne in particular has supported the view that the increased condenser potential is to be considered as due to the reaction of the armature current upon the field magnets. We have seen in the discussion of the clock diagram of electromotive forces given in Fig. 14, that when capacity is present, the phase of the current flowing into and out of the condenser is in *advance* of the phase of the impressed electromotive force. Since the maximum value of the impressed electromotive force coincides in time with the passage of a loop of the armature through the middle point between two alternate field poles, a very little consideration shows that a current flowing through the armature which is in advance of the impressed electromotive force in phase will be in the right direction to assist or strengthen the magnetism of the field magnets, and hence this current so flowing will act to increase the electromotive force of the machine by its reaction upon the field. Hence the condenser current shares with the exciting current the duty of magnetising the field magnets, and we can afford to reduce the strength of the external exciting current and still keep the dynamo terminal electromotive force constant if we add a capacity across its terminals. Under some circumstances the whole excitation could be conducted by the condenser current, and the alternator become self-exciting like a continuous-current shunt-wound dynamo.

If we consider the case of the experiment described in § 10, when external excitation and speed are kept constant and the capacity continually varied, it is easy to see that when the condenser capacity is made zero there is no condenser current, and hence no increase of magnetisation of field and no rise of pressure. Again, when the capacity has such a value that it exactly nullifies the self-induction of the armature, which happens when the quantity $C L p^2$ is unity, then the armature current is in consonance, as regards phase, with the impressed electromotive force;

and hence there can be no armature re-action and no increase of the magnetism of the fields. Between these two zero effects lies a maximum value. Referring again to the diagram in Fig. 15, it is easy to see that we can in imagination divide the current which is represented by one R^{th} part of O R into two components, one in consonance with the impressed electromotive force, and one in quadrature with it, or 90deg. ahead in phase.

This last component can be called the field-magnetising component of the current, for it is the magnitude of this component which determines the increase of the magnetisation of the field poles by the armature current. By drawing a series of diagrams, such as that in Fig. 15, with constant values of V_0, R, and L, but values of C increasing from zero to infinity, it is not difficult to see that a maximum value of this field magnetising component of the armature current will be found when the condenser capacity C has such a value as to cause the angle by which the phase of the complete current is ahead of the phase of the impressed electromotive force to be 45deg. The armature reaction theory therefore gives a general account of the experimentally proved fact that continuous increase in the capacity results in a rise of pressure at the condenser terminals up to a maximum, and finds the period of that maximum as corresponding with a certain definite advance of the current phase over that of the impressed electromotive force—viz., 45deg.

The self-induction theory is in a similar agreement as to the general facts, but it indicates that the greatest rise of pressure will take place when the condenser current phase is 90deg. ahead of the position which it would have when no capacity at all is connected to the dynamo terminals; and this condition is only consistent with the condition imposed by the armature reaction theory, for one particular value of the frequency—viz., when $T = \frac{2\pi L}{R}$, or when $Lp = R$, that is, when the angle of lag of the current behind the impressed electromotive force would be 45deg. if no capacity were present at all.

The armature reaction theory is therefore not identical with the self-induction theory. It may be that both effects are present at the same time; but which one is the truth, or how much of each is the truth, can only be settled by repeating such experiments as those made at Messrs. Siemens' Works (p. 395), and at the same time adapting to the alternator a phase indicator, which shall enable the phase of the current relatively to the impressed electromotive force to be determined, corresponding to each particular value to be ascertained.

That such effects of rise of pressure due to the combination of capacity and self-induction can take place when no such effect as armature reaction on field magnets is present is shown by the experiments of Hertz referred to in § 11 of Chapter V., Vol. I. If the reader will compare Figs. 28 and 29 in that section of the first volume with the curves plotted as the result of the dynamo experiments in § 10 of this chapter, he will see the remarkable analogy between the two. For a certain critical capacity Hertz found the spark length, indicating maximum potential difference, reaches a maximum, and no effects other than those due to electro-magnetic momentum and capacity can enter in this case.

When an alternator is attached to a transformer and the secondary terminals of the transformer connected to the poles of a condenser, then the rise of pressure found at the terminals of the condenser when the alternator is kept at constant speed and excitation are due to two causes: firstly, to an alteration of the change ratio of transformation of the transformer; secondly, to the armature effect just discussed, only in this case the condenser acts back through the transformer. The alteration of the change ratio of the transformer is due to the annulment of the "drop" due to magnetic leakage, and does not take place with every form of transformer. When a transformer is gradually loaded up and the secondary current increased, the magnetising effect of the secondary current upon the core is opposed to that of the primary, and the result is to develope magnetic poles in the core and create a leakage field whereby the total induction through the secondary is made less than the total induction through the primary, as the resistance of the external secondary circuit is reduced and the secondary current increased by loading up the transformer. If under these circumstances the ratio of the potential difference at the secondary terminals to the potential difference at the primary terminals is sensibly reduced as compared with the ratio when the secondary circuit is open, the transformer is said to have a "drop" in working. When a condenser is bridged across the secondary terminals the condenser current flowing into it is, as has been already explained, in phase in advance of the secondary electromotive force by 90deg.

It will be shown later on from what are called the Indicator Diagram of Transformers that the primary and secondary electromotive forces are opposite in phase, also that the phase of the magnetic induction in the core is in advance of the secondary electromotive force and in arrear of the primary electromotive force by about 90deg. Hence the phase of the condenser current or current flowing into and out of the condenser is in phase in agreement or is in near agreement with the magnetic induction, and hence occurs at a time which enables it to *strengthen* the induction in the core or in that part of the core enclosed by the secondary circuit. Hence this not only may compensate entirely for the "drop" if the transformer is sending out a work current from its secondary circuit, but it may even over-compensate and effect a still further increase in ratio of secondary electromotive force to primary electromotive force. If the transformer is one in which the primary and secondary circuits are so completely intertwined that no magnetic leakage is possible, then this alternation of change-ratio will not be found.* In this case $L N = M^2$.

Hence when alternators are coupled to mains having capacity through step-up transformers, the effects of increased pressure which is found when the mains are connected to the constantly excited alternator, is a mixture of two separate effects, one due to the action of the capacity on the transformer and one due to the action of the capacity on the armature of the alternator.

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* It was pointed out by Mr. Alexander Siemens, during a discussion at the Institution of Electrical Engineers on a Paper by the author on "Some Effects of Alternating Current Flow in Circuits having Capacity and Self-Induction," that in the case when experiments such as those described in §10, were made with a form of transformer which he calls a *cable transformer*, although rise of pressure effects were found at the two terminals of the transformer when connected with a condenser, yet the change-ratio of the transformer was not altered. In this form of transformer, which is an open magnetic circuit one, magnetic leakage is very small. See *Proc. Inst. Elec. Engineers, London*, Vol. XX., July, 1891, p. 456. The reader is referred to the whole of the above discussion for further interesting information.

The effect on the transformer has been particularly discussed by Prof. Ayrton and Dr. Sumpner in a Paper on "Alternate Current Interference."*

Their results were briefly as follows:—

(i.) Whether the transformation is up or down, the percentage rise of pressure in the secondary is greater than that in the primary.

(ii.) That these percentage rises diminish as the secondary current increases.

(iii.) That they increase with the ratio of transformation.

(iv.) That the rise on the secondary terminals may be considerable without that on the primary being appreciable.

(v.) That the rise in the secondary still may persist even when large secondary currents are taken out of the transformer.

In the transformer used in the above experiments the change-ratio was 1:2, and the maximum rise of pressure was 11 per cent. Dr. Sumpner also made some experiments to separate out the relative values of the effects of the dynamo and transformer in producing the increased pressure at the condenser terminals, and found the effects about equal.

Space forbids a more extended discussion here of these effects of capacity in circuits conveying alternating currents. If an open circuit possessing inductance and capacity, such as a long concentric cable, is acted upon by an alternating electromotive force at one end, it is possible, under some conditions, to have a progressive rise of pressure all along the cable. For a fuller discussion of these effects the reader is referred to a Paper by the author on "Alternating Current Flow," † and the advanced mathematical reader to a series of Papers by Mr. Oliver Heaviside on "The Self-Induction of Wires," published in the *Phil. Mag.* for 1886 and 1887, and more particularly to the Paper in the *Phil. Mag.* of January, 1887, Vol. XXIII., p. 18, in which the mathematical theory of the propagation of a variable current in a concentric cable is very ably discussed.

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* See *Proc. Physical Soc. of London*, February 27th, 1891; also *Electrician*, Vol. XXVI., p. 540.

† See *Proc. Inst. Elec. Engineers*, Vol. XX., July 1891, p. 362.

§ 13. Methods of Transformer Distribution. Sub-stations.—There are two methods in which transformers are employed in the distribution of electric current for public purposes. The first method may be called the method of *distributed transformers*, and the second the *sub-centre*, or *transformer sub-centre* system. According to the first method, every building or house to be lit electrically is provided with one or more transformers, which reduce the pressure of a current supplied at a high pressure, generally at 1,000, 2,000, or 2,400 volts, to 100 or 50 volts, as required for use with incandescence lamps. The high pressure current is supplied by a system of underground or overhead high-pressure service lines, and the necessities of each customer have to be considered in providing him with a group of one or more transformers for private use. In the second system the customers are not fed from private transformers at all, but draw their supply from a common low-pressure network of service conductors of greater or less extent, which is kept charged to a constant potential by means of a single central group or bank of transformers. Each of these methods has certain advantages. In commencing the supply of electric current to a town or a district of a large city, it has been generally found that at first the demand for light is sparsely distributed or not dense. That is to say, here and there people are found who will take the light, but whole rows of house holders do not at once demand it. Hotels, restaurants, public houses, and many large shops regard electric lighting as an advertisement and means of getting noticed. Hence they come forward at once and are ready to take it when it can be supplied at any reasonable price. The average householders, particularly of the middle class and the smaller shopkeepers, hang back (1) because of the initial outlay necessary in having the "house-wiring" properly done, which may be estimated at about 25s. per light for good work, and (2) because of the fact that the low price of gas, as in England, or mineral oils makes electric lighting at the present price of 7d. to 8d. per kilowatt-hour a rather more expensive form of illumination, and its additional advantages appeal less to them than does the immediate outlay. Hence the initial demand, though it may amount to a considerable total of lighting, exists in a more or less scattered form. This, however, is capable of being adequately dealt with by distributed transformers. The system is also a very flexible one, and when carried out by means of overhead conductors, changes and adaptations can readily be made as required in the conductor system. The advocates of low-pressure systems generally take occasion to point out that the cost of the transformers, when added to that of the high-pressure conductors, would bring up the total cost of the distribution system to about the same amount as the low-pressure conductors in an equivalent low-pressure distribution. It must be noted, however, that it is a much more easy task to proportion the initial outlay for conductors to the immediate requirements in the case of distributed transformers, than is the case in laying out a low-pressure service system, and that the economical disposition of low-pressure networks to cover large areas is a very difficult matter to effect when the amount of lighting and its distribution is a question, more or less, of conjecture. It is admitted, however, that the system of distributed transformers is an imperfect method, except in so far as the conditions inseparable from the initial stages of public electric lighting make it advisable to adopt it at the outset of the enterprise. The reasons are not far to seek. In putting in a transformer into the house of a customer it is necessary to select a size which will meet his *maximum* requirements. Hence, if his usual custom is to use a maximum of 30 lamps, but on some few exceptional occasions to use 45 lamps, then generally speaking a 50-light transformer would be put in. Moreover, transformers being only made in certain standard sizes, if his maximum lamps in use are, say, 17 in number, he would have to be provided with a 20 or 25-light transformer. Three things follow from this: first, the transformers all over the supplied area are, on the average, worked very considerably below their full capacity, hence arises, generally speaking, a very moderate or perhaps low efficiency of transformation. Second, there is an unproductive capital outlay in transformers, for, generally speaking, about 25 per cent. more total maximum capacity has to be provided than is represented by the total maximum number of lamps in use. Third, the transformers being always connected to the primary mains, take up and waste energy, even when no lamps are put on, this being usually called "the waste due to magnetizing current." It is difficult or impossible to make any general statements as to the total effect of these causes in determining the ratio between the total units of electric energy supplied to the primaries of all the transformers and that utilised on the secondary side; but the coal consumption of many stations working with distributed transformers shows that the ratio is, in some cases, as much as two to one; that is to say, one half the energy supplied by the dynamos is uselessly dissipated.

The system of distributed transformers has been properly called a good pioneer system, and it is not too much to say that without its employment one-half of the electric lighting supply business now existing could not have been built up. When this distributed transformer system is employed it is necessary to find on each customer's premises a place in which to instal the transformers. Some Supply Companies build a brick transformer house, a small fireproof structure, costing about on an average from £4 to £10, placed in some area, yard, or cellar. Others find a dry corner in some basement cellar or outhouse, and enclose the transformer in a watertight iron case and fix it to a wall. The transformer or transformers have then to be provided with a pair of primary fuzes, long enough to prevent an arc starting across the terminals, and a high-tension double-pole switch. On the low-tension side also has to be provided a pair of low-tension fuzes, a double-pole house or service switch, and an electric meter. Also the British Board of Trade require an "earthing" safety device to prevent the high-tension current ever entering the house conductors. In the overhead wire systems in use in America and elsewhere the transformer is frequently placed outside the house affixed to the roof or walls, and a lightning protector has then to be fitted.

In the sub-centre system or transformer sub-station system each consumer is electrically fed from an underground or overhead low-pressure service network, which is kept supplied at certain points by means of transformer centres. In carrying out this system in its most perfect manner the district to be lit should be mapped out into small areas of not more than 400 yards in diameter, that is, into circular areas of 200 yards radius or squares of 400 yards diameter. The centres of these areas should be chosen at points at which convenient rooms or transformer chambers can be obtained in which to locate the transformers. The transformer chambers may be excavations made below ground. In each of these areas low-pressure networks of conductors should be laid down. Since, at a current density of 1,000 amperes per square inch, the drop in volts in a copper conductor is 2½ volts per 100 yards, it is advisable to have the areas, if possible, rather smaller than the above-named size. To these low-pressure networks the house services are connected, and even quite small consumers of one or two lamps can be profitably connected in this case. Each consumer has simply a meter, low-pressure fuzes, and double-pole house switch installed on his premises. The centre of this network of low-pressure conductors, or the feeder conductors of this network if they are employed, is joined to an omnibus bar in the sub-station, to which can be connected at pleasure any or all of a group of transformers placed in the sub-centre. These transformers all take primary current from a high-tension primary main which enters the room, and by means of suitable switches each transformer can be disconnected or connected on its primary and on its secondary side to the primary and secondary omnibus mains (*see* Fig. 25). The separate secondary networks may be all kept perfectly independent of each other, or they may, as suggested by Mr. Swinburne, be joined together by 1 to 1 transformers enclosed in iron boxes

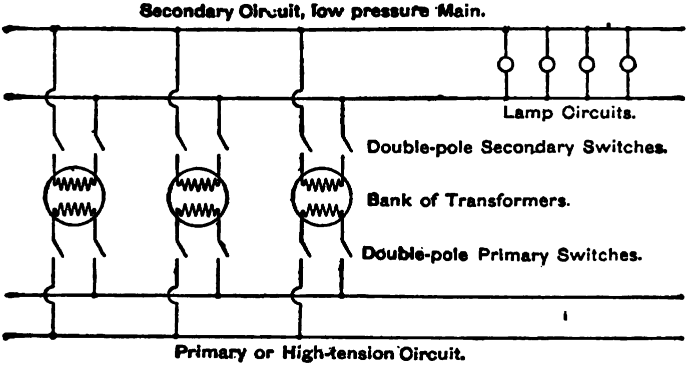
Secondary Circuit, low pressure Main.
Lamp Circuits.
Double-pole Secondary Switches.
Bank of Transformers.
Double-pole Primary Switches.
Primary or High-tension Circuit.

FIG. 25.—Arrangement of "Bank" of Transformers on Primary and Secondary Omnibus Bars.

buried in the ground. The district to be lit is, therefore, served with a series of high-pressure trunk lines radiating from an "eccentric" station, each of which terminates in a transformer house or chamber, as above described. These transformer houses can, if the soil is dry, be excavations in the ground, or subterranean rooms reached by an iron door and ladder. The immense advantage which this system has is that the supplied area is cut up into sub-areas of supply, of which the networks are all completely independent. A fault, or "dead earth," on one secondary network does not affect the others. Moreover, the total transformer power can be much more accurately proportioned to the maximum lamp-load, and small consumers can be profitably supplied. If these sub-stations each supply enough lights to make it worth while to keep an attendant at them constantly on duty, he can connect or disconnect the transformers as required in such wise that the transformers connected to the system are always kept fully loaded. In this way the waste of magnetising energy can be saved and the efficiency of transformation kept up. Generally speaking, however, it would not pay to keep an attendant at all the sub-stations, and hence devices have been invented to supply the necessary attention by means of an automatic switch. These devices have not as yet been extensively employed, for the simple reason that in hardly any case at present (1891) has this transformer sub-system method of distribution been carried out in a complete manner; that is to say, completely, and with a careful and deliberate design. Nearly every transformer supply system has begun on the distributed transformer method, and continued it when begun.

In laying out a transformer system on the distributed transformer method the engineer should have regard to the possibility of converting it subsequently into a sub-centre system, and a little forethought in selecting routes and lines for the main high-pressure conductors will enable this to be done. In no case with which the author is yet acquainted has the sub-station system been adopted and worked for a sufficient time to enable a proper comparison to be made between the true commercial results of alternate current and direct current methods of supply, taking the best possible instances of both kinds. Many stations exist for the supply of direct current which are almost ideal in their perfection of working and design, and in which the efficiency of generation and distribution is accurately known. That is to say, the units of electric energy produced at the dynamo terminals per lb. of coal used is known, and the ratio of the units sold or delivered to customers to the units generated, called the *efficiency of distribution*, is also known accurately for each month of the year. No such information is yet forthcoming for a good case of a transformer sub-centre system of supply. It is manifestly unfair to institute comparisons, as is often done, between highly perfect systems of direct current supply and imperfect distributed transformer systems, with very poor efficiency of distribution. It appears probable that with transformers as now made, used on the distributed system, and kept connected all the 24 hours to the primary mains, the mean annual coal consumption is about at the rate of 20lb. per unit of electric energy sold; whereas in the good direct current supply systems it does not exceed 10lb. There is no reason why a well-designed system of transformer sub-centres should not exhibit a coal economy quite equal to that of any direct current system, and be possessed at the same time of much greater flexibility and power of extension, as well as of all the advantages derivable from a generating station situated in the best position outside the area of supply. In such case the secondary networks can be laid down on the three-wire system, and thus the economical area of low-pressure supply increased beyond a radius of 200 yards. A beginning has been made in adopting this sub-centre system at Rome, and some electric stations in England are being projected and designed on this plan. The full advantages of this sub-station method are only to be derived if the transformers are disconnected from the mains when not fully loaded, so as to curtail the waste of magnetising current. This can occasionally be done by hand by switches operated from the outside of the transformer room as at Rome, but the desirable thing is that it should be accomplished by automatic switches.

It is impossible within the limits of this chapter to fully discuss all the arguments for and against the transformer sub-system method of working. Mr. Kapp first strongly advocated this mode of distribution in 1887 in a Paper in *Industries*, on December 2nd, 1887. Mr. Crompton also fully discussed it in his paper on "Central Station Lighting." (See *Electrician*, Vol. XX., p. 634;* also *Journal Soc. Tel. Eng.*, Vol. XVII., p. 350.) And Mr. Swinburne has also advocated its employment in a Paper on "Transformer Distribution," read before the Institution of Electrical Engineers on February 19th, 1891. (See *Electrician*, Vol. XXVI., p. 547; also *Proc. Inst. Elec. Eng.*, Vol. XX., p. 163.)

§ 14. **Automatic Change-over Switches.**—Many inventors, such as Mr. Ferranti, Mr. Mordey, Mr. Kapp, and Mr. Tomlinson, have applied their ingenuity to devising automatic switches which shall connect or disconnect transformers from a common bar according as the secondary load is varied. The idea embodied in these appliances is to provide each building or customer or group of customers or sub-station with two or more transformers. A small transformer just equal to doing the daylight work which is always connected to the mains, and a larger transformer designed for high economy which is put on or off automatically as the load varies. This change is intended to be effected by an automatic change-over switch, which is operated by the current from the little transformer. When the secondary current taken out of this last is increased beyond a certain limit it is made to actuate a relay which closes the circuit of one or other of two electro-magnetic solenoids or starts a motor, and this motor or magnet is intended to close a switch and throw in a large transformer.

The perfecting of such an apparatus, if it can be accomplished, would provide a means whereby the efficiency of distribution of a distributed transformer system could be brought up into line with that of a direct current station. It is generally stated that the loss of energy by the continuous flow of magnetising current shows itself in a marked manner in the coal bills of a distributed transformer system station; and there is reason to believe that the allegation has considerable truth.

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* A long and ardent discussion followed the reading of Mr. Crompton's Paper, in which the use of transformer centres was chiefly advocated by Mr. Kapp. Mr. Kapp read also in the same year (1888) a Paper on "Transformers" (see *Journal Soc. Tel. Eng.*, Vol. XVII., p. 117), in which he also referred to the same matter.

Mr. Tomlinson's automatic switch is in principle as follows:—A bank of, say, five groups of transformers of equal capacity is arranged. One group of these is permanently connected to the primary omnibus and secondary omnibus mains of the sub-station. The automatic regulator consists of a series of four double-contact switches, which put each of the other groups into connection both on the primary and on the secondary side as the demand for current requires. The switches, which throw in the transformers, are turned over by a carriage in the form of a double wedge, which runs backwards and forwards along the bed-plate of the machine; and, as it passes, each switch throws over a tumbling lever, which strikes the switch into or out of action.

As the primary and secondary circuits are broken together, there is little or no spark.

This carriage is moved by an endless chain actuated by two weights, which are released respectively by two electro-magnets. The large weight, which takes the transformers out of circuit, has to be wound up once a week, and, as it takes out the transformers, it at the same time winds up a smaller weight ready to put them in again. If any failure whatever of the large driving weight occurs, or if the attendant forgets to wind it up, the small weight is always ready to put the whole of the transformers into circuit, and must do this before the apparatus becomes inoperative.

The mechanism is started by an electro-magnetic release, which is worked from the generating station by a special wire. A double relay is provided, placed in the secondary circuit of the fixed transformers. As soon as the current exceeds full load a contact is made, and a small current is sent through one of the magnets of the apparatus along a wire to the central station, where it passes through a choking coil and a bell. On the bell ringing, the attendant knows that more transformers must be put in, and he puts down a switch, which short circuits the choking coil and bell, and allows a sufficient current to pass to actuate the magnet and put a sufficient number of switches in. If the attendant should inadvertently hold down his contact-key too long the mistake will be corrected by the apparatus, as the circuit will break at the relay, and the machinery will cease to act. The magnet for taking out transformers is actuated in a precisely similar manner by the other part of the relay, which acts when the current in the fixed transformers falls to less than half load.

Mr. Kapp's automatic switch is shown in general design in Fig. 26. In this appliance, as in Mr. Ferranti's switch, there is a small transformer, T_1, permanently connected to the mains. If the secondary current going out from this exceeds a certain value, then a relay magnet and motor, M, are energised, which

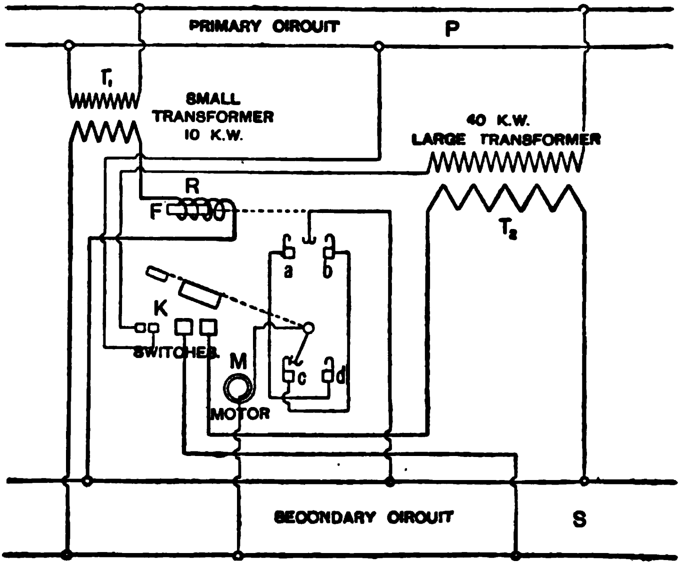

FIG. 26.—General Plan of Connections of Mr. Kapp's Automatic Transformer Switch.

throws over a contact, and puts in another group of transformers, T_2, by closing a double switch K.

Some such apparatus as the above described will have to be employed in connection with transformer sub-stations, in all cases in which transformers are employed, which have not very high efficiencies at low loads, to avoid the waste of energy caused by the core hysteresis during all the 24 hours.

Many engineers, whilst admitting that apparatus of this kind can be got to work, do not look with much approval upon automatic machines, which, however perfect in principle, are yet not invariably found to act as perfectly in practice.

Accordingly, some makers of transformers, like Mr. Mordey, look for a way out of the difficulty by designing transformers having small internal waste. It is not beyond possibility that some way may be found of annulling the effects of hysteresis in the core, and thus rendering unnecessary the severance of the transformer during light hours of work. The possibility of employing automatic switches to throw on and off transformers has been demonstrated in practice on a small scale, but it remains to be seen how far they are absolutely to be depended upon in extensive use.

§ **15. Safety Devices.**—It is not an uncommon thing for the high-pressure current to rupture the insulation of a transformer and make connections between the high and low pressure coils. A discharge may take place between one end of the high-pressure coil and the iron core, or one or more high-pressure coils may get short-circuited, and in this case the insulation of the high-pressure coil gets destroyed. If this happens, the low-pressure coils also get injured and the final result may be that one or both sides of the secondary coil becomes connected to the high-pressure circuit. Under these circumstances anyone touching the secondary circuit or any lamp or fitting might receive a shock injurious or fatal. Accordingly, it was early seen that in transformer working it would be necessary to introduce some form of safety device which should render it impossible for unpleasant results to happen under any such circumstances.

In 1888 Major Cardew brought forward the first design for such a safety device,* and has subsequently improved it. The nature of this device consists in providing a means by which, whenever the secondary circuit is raised in potential above the earth by say 400 volts, the secondary circuit is automatically put "to earth." As long as the potential of the secondary circuit does not exceed or fall below that of the earth by a dangerous amount, the secondary circuit is insulated, but on that amount being exceeded a good contact is made between it and the earth. The device as shown in Fig. 27 consists of two brass plates placed near but insulated from each other. Between these lies a thin foil of aluminium which is retained in position by ebonite pegs. One plate is connected to earth and the other to the secondary circuit. A flat projection is formed on the upper plate over one end of the foil, so that as soon as a difference of 400 volts is established one end of the foil lifts by static attraction and a metallic contact is made between the two plates. The main primary fuses are then immediately severed by the increase of current, and the supply cut off. The two plates are insulated by ebonite rings and are securely bolted together, so that after being tested no skill is required to fix them. These plates are carried by brass clipping springs, to which the connections are permanently made, so that the act of sliding in the discs makes the necessary connections. It is evident that the apparatus can be modified to act as a relay and cut off both poles of the secondary if required. This apparatus, called an "earthing device," has been extensively used in connection with transformer systems. Other means have been from time to time suggested to obviate the danger arising from a possible invasion of the high-pressure current into the secondary wires. One of

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* See *Journal Soc. Tel. Eng.*, Vol. XVII., 1888, p. 179.

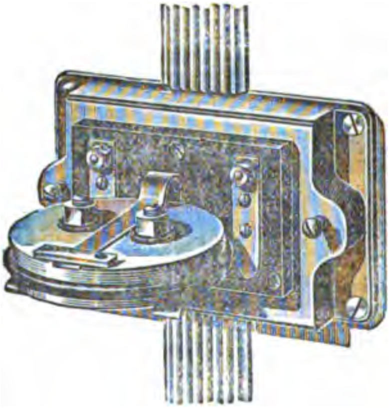

FIG. 27.—Major Cardew's "Earthing Device" for protecting Transformer Circuits.

the first of these is that of "permanently earthing" the secondary system on one pole. This was apparently first suggested by Prof. Elihu Thomson in 1885,* and again independently by the author in 1885. Profs. Ayrton and Perry claim, however, to have used the device as far back as 1883. The argument in favour of earthing the secondary circuit is that, being so permanently connected to earth, it is impossible for the circuit as a whole to be raised or lowered below the earth in potential. Against this it is said that earthing the secondary circuit introduces another danger, in that only one other earth is then required on the secondary circuit to produce a "dead cross" or short circuit, and that dangers from fire are thus increased. The insurance offices and British Board of Trade have decided not to permit this method.

Another method described by Prof. Elihu Thomson in 1886, and subsequently by Mr. Kent, is to introduce a metallic sheath properly slit between the primary and secondary coils of the transformer and to connect this sheath to earth. A third and better method employed by the Thomson-Houston Company is to use a *film cut-out*, that is a thin prepared piece of paper placed between two metallic contacts, and which paper is pierced when the pressure between these contacts exceeds a certain amount. In using this film cut-out a pair of films are placed on either side of a contact plate connected to earth, and outside these films plates connected to the two secondary conductors. Thus each side of the secondary circuit is only separated from an earth connection by means of a thin film which can be arranged to be perfectly insulating at 100 volts but to pierce directly if subjected to 1,000 volts. In case of invasion of the low-pressure circuits by the high-pressure current this film is pierced on one or both sides and puts the secondary wire to earth, at the same time causing the primary fuses to "blow out."

One great feature of the sub-centre system is the abolition of all special devices of this kind on customers' premises, and the substitution of one single similar device at the sub-station, where it is under the immediate constant inspection of an expert.

Mr. Ferranti has designed an ingenious device for guarding against the risks of an "earth" on one side of the secondary system. Suppose that a transformer is feeding a house circuit from its secondary terminals, and that an "earth" is made on one pole. This is a potential danger, in that it only requires one other "earth" in order to establish a dead cross on that secondary circuit, and hence perhaps cause a fire. In order to indicate a partial "earth" on the secondary circuits, the following arrangement (shown in Fig. 28) is adopted :—

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* E. Thomson's United States patent, No. 322,138, April 27, 1885.

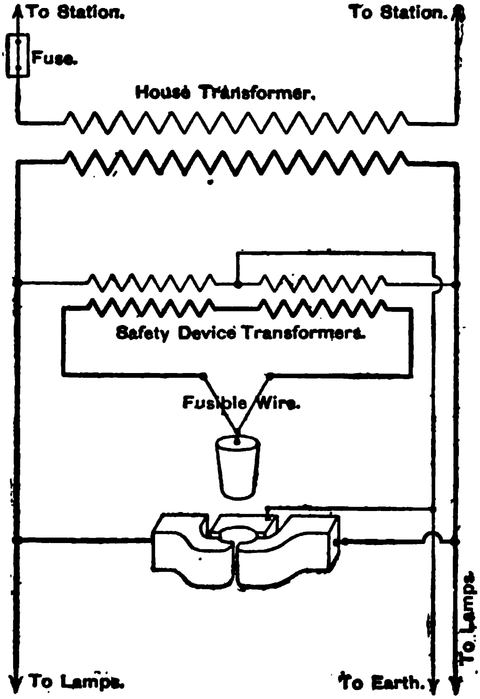

FIG. 28.—Ferranti "Earthing Device" for Transformer Protection.

Across the secondary main is placed a pair of small transformers, the primaries of which are in series and the secondaries of which are in series, but so joined that the secondary electromotive forces of each oppose each other. The middle or junction point of the primary circuits of the two small transformers is put to earth. The secondary circuit of the small transformers is completed through a small fuse wire, which holds up a conical weight. If one side of the secondary mains is put to earth, fully or partially, then one of the little transformers ceases to produce current, and the balance of electromotive forces in the secondary circuits being upset the fuse wire is traversed by a current and melted. The conical weight then drops, and is made to fall into a split cup consisting of three contacts, two being connected to the secondary mains and one being "an earth." The secondary mains are thus both dead earthed, and the main fuses on the primary of the supply transformer blow out. Thus the apparatus reveals partial earth on the secondary circuits; and if the resistance of these earths is below a certain amount it makes it known by putting the lights out.

§16. **Choice of Frequency.**—In connection with an alternating current station the selection of the frequency of alternations at which to work is important. The most usual working frequencies range from 40 to 130 complete alternations. American practice favours the higher number. This is done because it enables small transformers to be built with a moderate amount of iron in the cores, giving at the same time a small magnetising current. This is advantageous for systems of distributed transformers. The American system of transformer working is to employ as far as possible small transformers working on separate secondary circuits on which all the lights are generally all "on" or all "off" together. Hence, "secondary drop" becomes relatively unimportant, whilst a reduction of magnetising current is very important from the point of view of plant efficiency. In the Ganz stations in Europe the lower frequency is adopted, on account of the greater facility that it gives for working the alternators in parallel, and also giving slower dynamo speeds, thus admitting of direct driving. The English practice is to get in between the two limits and to take 80 to 100 as the frequency. There is no doubt, however, that the tendency is to lower alternations. Low frequencies not only mean greater ease in parallel working of alternators, but mean greater ease of motor working for small and large motors. By a suitable proportion of iron in the transformer cores, the magnetising current can be kept down; and as the future of alternate-current working will certainly be in the direction of employing economical large transformers in substations, the question of bulk of transformer will not be material. It is not improbable that a frequency of from 40 to 50 will be found in the long run to be the best in every way, when two-current alternating-current motors are perfected for use on ordinary alternating-current circuits.

§ 17. **Regulation of Pressure.**—In any system of electric supply for lamps arranged in parallel it is, or ought to be, in the power of the superintendent of the generating station to keep as nearly as possible a constant potential between the terminals of all the lamps. That it shall be possible to do this necessitates careful prevision in the design, and in many existing alternating-current stations much is left to be desired in this respect. In a system of distributed transformers, between the lamps and the dynamo three causes of variation of pressure exist, even assuming constant pressure kept at the terminals of the dynamo. First, there is the "drop" in pressure in the primary leads between no current and full current in the primary circuit. This can be, and is, generally kept within two per cent. Second, the "drop" in the transformers between no load and full load; and, lastly, the "drop" in the house wiring. If the drop in the transformers does not exceed four per cent., which is not always the case, and if the drop in the house wiring is not more than two per cent., we have a total possible drop in pressure at the lamp terminals of eight per cent. between no load and full load, even if the pressure at the station is kept constant. There are many cases of such alternate-current supply, in which the variation would amount to ten or twelve per cent. If all the transformers had loads imposed equally at the same instant, and were all of the same size, it would be possible to regulate the pressure at the station to so vary with the outgoing current that the pressure at the lamps is kept constant. This is roughly done in practice at some alternating stations by providing the engineer in charge with a table of amperes and volts, showing at what pressure the supply should be given at the station, corresponding to a given total output in amperes to maintain pressure at the lamps fairly constant, this table of values having been determined by experiment. The real difficulty, however, lies in the fact that the transformers are not all equally loaded, and that hence variations in pressure occur over the district. On the distributed transformer system it is very difficult to do more than attempt to keep a kind of average constant pressure, and to aid the result by the employment of transformers having as small a secondary drop as possible. It is a good plan to so select the voltage of the lamp that the standard pressure is kept when the transformer is about half loaded. The extreme range of drop of the transformer is then split into half above and half below the normal pressure. If, for instance, the drop in a transformer is four per cent., and the transformer is so wound as to give 100 volts at half load, and supplies 100-volt lamps, then the extreme variation of pressure on the lamps between full load and no load will be from 98 to 102 volts, and the effect on the lamps will not be so noticeable as if the transformer was wound to give its normal voltage at full load, and hence to rise four per cent. when not loaded at all. In Chapter II. have been described various methods by which pressure can be maintained constant at the far end of primary circuits independent of load. It is quite possible, both by the methods employed in the Ganz system or in the Thomson-Houston system, to slightly *over compound*, or over compensate for the drop in the primary lines, and to do this to an extent which will nearly annul the drop in the transformers. That is to say, the pressure at the terminals of the primary circuit of the house transformers is made to slightly increase at the time when the majority or all of the transformers are fully loaded. If these house transformers are all under pretty much the same circumstances, it is possible to secure a fairly constant pressure at the secondary terminals.

On a well-laid-out system of transformer substations far better regulation could be kept. In the first place, each secondary network would be laid out with feeders of such capacity that the loss of pressure in the secondary mains could be made negligible. By a proper process of connecting and disconnecting the transformers according to the variation of load, and by the employment of transformers with very small secondary drop, it would be possible to preserve a very uniform pressure on these secondary networks. By proper regulating apparatus at the generating station, the primary pressure at these substations could be kept constant and regulation of secondary pressure secured within one or two volts on each side of the standard. Irregularity of pressure supply not only affects most injuriously the life of incandescent lamps, but it deprives incandescent lighting of one of the chief charms which it possesses when properly regulated, viz.—a light which is absolutely steady and calm, and hence restful for the eyes.

CHAPTER IV.

THE CONSTRUCTION AND ACTION OF TRANSFORMERS.

§ 1. **The Practical Study of the Transformer.**—Previous pages have been occupied with the historical development and modern use of transformers in electrical distribution. The attention of the reader will in the present chapter be directed to questions of the construction and the mode of action of transformers as at present made. In order that improvements may be effected in any acting appliance it is essential that its true method of working should be properly explored. In improving the steam engine, James Watt felt the importance of this procedure; and hence invented the admirable device called the steam-engine indicator, which provides a means by which the engineer can, as it were, look inside the steam-engine cylinder when the engine is working and discover the nature of the actions therein going on. In the same way a true practical knowledge of the transformer can only be obtained by the application of some method enabling the relation of the various currents, electromotive forces, and the magnetic induction to be definitely known. Considerable attention has been devoted to this matter of late years, and the results of such examinations are highly interesting. In order to discover what is actually going on in the circuits of a transformer we must have the means of determining at every instant the true instantaneous values of the currents and electromotive forces and of the magnetic state of the core. This necessitates that we shall be able to describe or delineate the curves representing the changes of current strength and the changes of electromotive force or induction. Several methods have been devised in which by optical methods an insight can be gained into the form and position in relation to each other in time occupied by these curves. Some of these will be described presently. Meanwhile, we may say that up to the present the most useful information has been gained by the application of a method apparently first suggested by M. Joubert in July 1880, and subsequently employed by Dr. Louis Duncan* for plotting down the form of the wave, either of electromotive force or current of an alternator. A general idea of the experimental means by which the exact law of variation of the current or electromotive force in an alternating current circuit can be obtained, is as follows.

Suppose the end of the shaft of an alternator to be provided with a projecting pin which is insulated from the shaft, but connected by a wire with one collar or terminal of the armature. Let an insulated spring be so adjusted that this pin just touches it at one instant, when carried round by the shaft, and let the spring be capable of movement so that the instant of contact at each revolution of the shaft can be made to take place at any assigned position of a certain bobbin of the armature with reference to the field-magnet poles. Let one terminal of an electrostatic voltmeter or electrometer be connected to the spring, the other terminal being connected to the end of the armature and which is not in connection with the pin. Imagine the armature set in rotation, then the pin makes contact at one definite instant in each revolution corresponding to one definite instantaneous electromotive force in the armature. Hence the voltmeter is as it were connected for an instant repeatedly to a definite source of potential; and if the speed of revolution of the dynamo is sufficiently great the voltmeter or electrometer will show a definite deflection corresponding to the electromotive force in the armature at the instant of contact. By moving the spring into positions in which the contact is made at equidistant positions of the armature loop from its position of zero electromotive force, we can determine and plot down to scale the instantaneous values of the electromotive force during one entire period or cycle of the electromotive force variation. We thus can obtain a graphic representation of the electromotive force or current wave. In order to obtain current curves we have only to apply the same method to measure the potential difference at the ends of a non-inductive resistance inserted in the circuit. By thus employing a revolving contact made momentarily at definite positions of the armature loop as it moves through the exciting field, we can pick out and measure instantaneous values of this current and electromotive forces of the circuits of a transformer fed by that armature, and thus construct a series of curves from these instantaneous values which give us the form and relative position of the waves of current and electromotive force. Such a set of diagrams is conveniently called a *transformer indicator diagram*, and it serves, after the manner of a steam indicator diagram, to give us real information about the actions going on in the interior of a transformer when at work. This method has been particularly put in practice by Prof. Harris J. Ryan in the United States, and in what follows we shall draw largely and almost verbally from an interesting monograph of his on Transformers.*

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* See a Paper by Dr. Louis Duncan and Messrs. Hutchinson and Wilkes in the *Electrical World* of New York for March, 1888, referred to in *The Electrician*, Vol. XXI., p. 111, on June 1, 1888. M. Joubert's experiments are described in the *Comptes Rendus* of the French Academy of Sciences for July, 1880, (Vol. XCI. p. 161, 1880.) M. Joubert employed a Siemens alternator, and showed how the instantaneous values of the current and electromotive force could be obtained.

Prof. Ryan in the first place improved and adapted the quadrant electrometer for the object he had in view. The essential features for an electrometer for these purposes are that it shall read with accuracy through a very wide range. Its indications must be unvaried by the absolute potential to which it is subjected as a whole. Its law must be perfectly definite, and it is also desirable that its constant be unchanging.

Fig. 1 illustrates this instrument in diagram. It consist essentially of a cylindrical electrometer needle and metallic quadrants E. D. To the upper side of the electrometer needle is attached a magnetised steel mirror that acts as a magnet and as a mirror for observing the position of the same. The needle is hung by a single silk fibre, H, from a hook in the top of the case, as shown. Metallic contact from the needle to the case is made by means of a platinum wire, ·0002in. in diameter. This wire is readily provided in the desired form by using the platinum cored silver wire that is supplied by makers of surveying apparatus. It is cut the desired length, and hooks bent into shape at its terminals. By immersing all of it but the hooked terminals in nitric acid, the silver is dissolved away, leaving the fine platinum core terminated by the two silver hooks. One end of this platinum wire thus prepared is linked into a hook into the top of the electrometer case and the other end into a small ring formed by a twist of the aluminium wire that surrounds the mirror C. The electrometer case is circular, and the above needle and quadrants are arranged so that the magnetised mirror is at the centre of the case, and the needle and quadrants below it. About the case, as the figure indicates, is wound a coil, B, of rather fine insulated copper wire. The magnetic mirror and this coil then, when the latter is in the magnetic meridian, constitute an arrangement similar to that of a tangent galvanometer. In the electrometer, the needle case and one set of quadrants are connected together and form one terminal, and the other set of quadrants, being connected together, form the other terminal of the instrument, in the

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* See *Transactions of the American Institution of Electrical Engineers*, Vol. VII., Jan., 1890. Prof. Harris J. Ryan on Transformers.

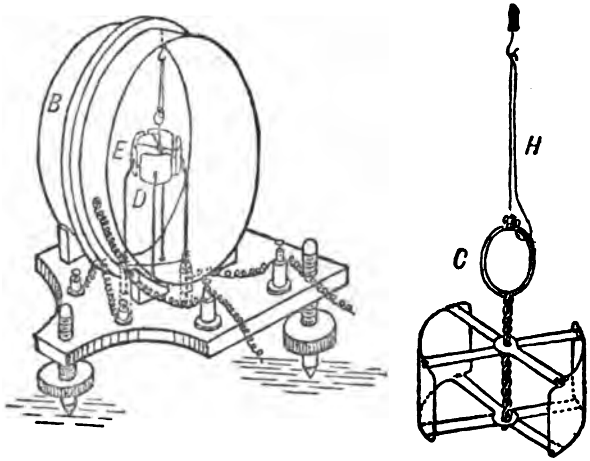

FIG. 1.—Ryan Combined Electrometer and Galvanometer.

manner set forth in the diagram. Thus, when the electrometer terminals are subjected to a difference of potential, the needle is acted upon by a couple brought about by the electrostatic forces, and is deflected from its position of equilibrium. Then, as is shown in Fig. 1, current from a Daniell's gravity cell in circuit with a suitable rheostat is sent through the coil on the electrometer in such a direction that the needle is brought back to its zero position by the action of the current in the coil on the magnetised mirror. The current is then further adjusted until the needle stands balanced at zero under the mutual action of the electrostatic and the electromagnetic forces. Under such circumstances the difference of potential of the electrometer terminals is proportional to the square root of the strength of the balancing current.

If we can, as was the case when the measurements here presented were made, consider the E.M.F. of our cell constant, the difference of potential is likewise proportional to the square root of the reciprocal of the total resistance in circuit with the cell. Parallel readings, taken with a standard voltmeter throughout a range varying from 3 to 600 volts, gave confirmatory results, showing no deviation from the above law and an unvarying constant. On account of the metallic case and its connection to the rest of the apparatus, the indications of the electrometer are, so far as could be observed, entirely independent of the absolute potential to which it is subjected as a whole. When contact was made with the alternator intermittently, and the electrometer charged to the potential difference to which its terminals were then subjected, it was found that considerable part of the charge was dissipated by leakage during the course of a revolution of the armature, no matter how good the insulation of the apparatus might be. A one-half microfarad mica condenser was then placed in multiple arc with the terminals of the electrometer. After a few revolutions of the armature the condenser became charged to precisely the same difference of potential existing at the terminals of the electrometer when the rotating edge on the armature passed the tip of the tongue on the shaft.

Under these circumstances the leakage that occurred was entirely negligible as compared with the charge in the condenser during the course of time required for the armature to make many revolutions. Thus arranged, the electrometer would give accurate readings of the instantaneous primary and secondary E.M.F.'s or primary current corresponding to the instant of connection of its terminals with the alternator. Again, the square root of the mean square of any of these values could at any time be read from the electrometer by short-circuiting the contact apparatus, and cutting out the condenser.

Being thus provided with an electrometer, the scale readings of which were known in volts, the next step was to arrange an apparatus by which this electrometer was connected to the terminals of an alternator for a small fraction of a second at each revolution exactly at an assigned position of the armature in its progress through the field. A point on the armature of an alternator always passes a fixed point at a time corresponding to a definite instantaneous value of the varying E.M.F. or current in it, no matter whether we regard these quantities in the armature or in the transformer primary or secondary circuit so long as the conditions remain constant. These experiments were only concerned with the values of the E.M.F. impressed at the terminals of the primary circuit, of the transformer or with the primary current and the secondary E.M.F.; hence by changing the position of the fixed point relative to the machine, the rotating point of reference in the armature would pass the new position of the fixed point at corresponding different values for the primary E.M.F., primary current, and secondary E.M.F.

In Fig. 2, B L is a prism of ebonite, bearing a projecting strip of brass, B, of which the upper side is filed to a dull edge. This edge is taken as a fixed point on the armature. An arm, F D, is arranged to rotate about D as a centre, which point is in line with the axis of rotation of the armature. A semi-circular board of hard wood, attached rigidly to the dynamo frame, serves both as a support for this arm and a circumferential scale whereby the position of the arm may be observed relatively to the machine. The arm is made of brass and given the form shown in the figure. It was bent into a U shape at the top, so as to pinch the board and thus remain fixed in any position desired. At the top of this arm is mounted a bar of ebonite, projecting towards the dynamo parallel to the armature axis. On its under side, fastened at G, is a brass strip, a tongue, H A, of spring brass is attached at the end and at right angles to the brass strip H G, as shown. The position of this part of the apparatus is carefully adjusted so that the point about which the arm rotates is in line with the axis of rotation of the armature and the sharply upward curved end of the tongue H A, just over the edge at the brass strip at B. Then when the armature is rotated the strip H G may be bent inward radially by turning the thumb-screw N, until the tip of the tongue A is heard to just lightly touch the edge at B as it passes. The arm may then be adjusted by hand so that the tongue will touch the fixed edge on the armature at any desired phase of the primary E.M.F., primary current or secondary E.M.F. and current. Coaxially with the armature a small brass rod is mounted on the bar of ebonite B L. It is connected metallically to B by means of a wire. At O, on the frame-work supporting the semi-circular board, &c., is mounted another piece of ebonite, insulating and supporting the thin metallic strip, P C, that bears against the above brass rod. G and I then are the terminals of this contact apparatus.

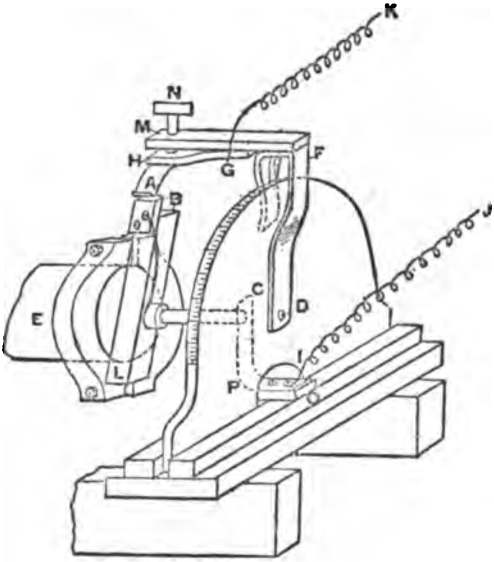

FIG. 2.—Revolving Contact Breaker on Armature Shaft of Alternator.

In Fig. 3, F is a non-inductive resistance, in series with the primary of the transformer under test. At A is the apparatus described in Fig. 1, and E is the above described electrometer reading through a wide range.

The terminals of the above non-inductive resistance and those of the electrometer are connected together through the contact apparatus at A. Then it must be evident that the electrometer will become charged by a difference of potential equal to that existing between the terminals of the non-inductive resistance at the instant that the fixed edge on the armature shaft passes the tip of the tongue in the apparatus at A. By reading the indications of the electrometer, therefore, and knowing the value of the non-inductive resistance E F, the instantaneous value of the primary current corresponding to the particular phase due to the position of the arm in the apparatus at A becomes known. In a similar manner the primary and secondary E.M.F. can be observed by changing the connections at G^1, G^2, G^3, G^4. Then the arm is rotated to another position, corresponding to a different phase, and the corresponding values of E.M.F.'s and current again observed as before. In this manner we proceed at equal intervals, sufficiently near, so that a curve may be determined by the values

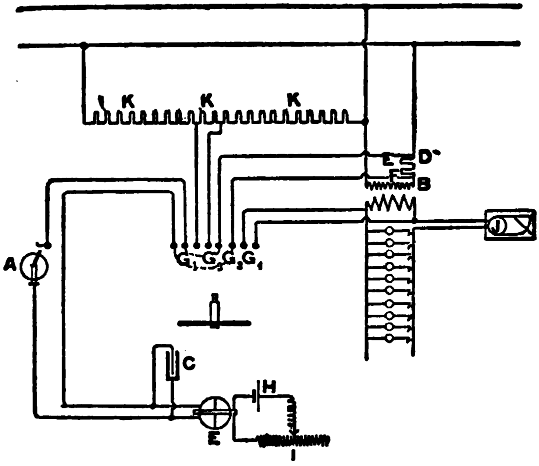

FIG. 3.—Arrangement of Connections in Ryan's Experiments.

thus observed at the several intervals, and that the instantaneous values of the E.M.F.'s or currents be accurately known at all times throughout a complete period.

For the purpose of obtaining the curve of impressed E.M.F. and the $\sqrt{\text{mean}^2}$* of the same, twenty-two 50 volt lamps were put in series across the primary circuit. The $\sqrt{\text{mean}^2}$ of the impressed E.M.F. in the primary was then obtained by reading, by means of the electrometer with the condenser cut out and the commutating apparatus short circuited, the $\sqrt{\text{mean}^2}$ difference of potential existing between each set of two lamps. In this way 11 readings were obtained, the sum of which was the total impressed E.M.F. This served as a calibration of the non-inductive resistance formed by the lamps. At the same time that these observations were made, two lamps were determined upon to be used in all subsequent observations on the total E.M.F. Knowing, then, from these comparative readings the ratio of fall of potential over two lamps, to the fall of potential over the whole twenty-two lamps, it was possible to determine the instantaneous value of the whole primary impressed electromotive force by readings taken of the instantaneous potential difference at the ends of two of the lamps, and thus obtain the curve of primary E.M.F.

Two 50-volt lamps were also placed in series with the primary circuit of the transformer as a non-inductive resistance, and, as previously stated, the $\sqrt{\text{mean}^2}$, and the values corresponding to any particular phase of the fall of potential through these lamps were observed. This gave a measure of the $\sqrt{\text{mean}^2}$ or any particular value corresponding to a particular phase of the primary current, when the resistance of these lamps was known at the temperatures to which they were brought by the current. A curve of resistance corresponding to the range of currents through which these lamps were used was determined carefully by Mr. Merritt at the Cornell magnetic observatory.

In series with the secondary circuit was placed a gravity ammeter containing a few small turns, and correct in its adjustment. It indicated the $\sqrt{\text{mean}^2}$ in the same way that an electro-dynamometer would have done. The observation of the various values of the secondary E.M.F. required no special arrangement—this was done direct in all cases. Since the secondary was always at work on a circuit possessing almost no inductance, no determinations of the curve of secondary current were made, for it would obviously have been found to be so nearly in unison with the secondary E.M.F. and possess all the characteristic variations of the same. The $\sqrt{\text{mean}^2}$ of its value was always known from the indications of the ammeter. As a load for the transformer, ten 16-candle power 50-volt lamps were provided which could be turned on and off as desired, and they were placed at an average distance from the transformer of not more than five feet.

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* This symbol, $\sqrt{mean^2}$, stands for the square root of the mean of the squares of all the instantaneous values observed at equal intervals of time throughout a complete period.

G^1, G^2, G^3, G^4, represent, in Fig. 3, the various terminals conveniently arranged on a switch-board for ready adjustment for any desired set of connections. The adjustable resistance at I consisted of a plug resistance box, enabling one to get any number of ohms in circuit from 1 to 100,000. It was very conveniently arranged; but a suitable slide rheostat and a damped magnet on the electrometer needle would have greatly facilitated the rapidity with which observations could be taken. The mode of procedure was to set the brush on the contact apparatus at some suitable point, and then corresponding to this point readings of the instantaneous values of primary E.M.F. were made. When lamps were turned on in the secondary, the ammeter in that circuit was also read. The brush was then moved forward to a new position and the above readings repeated. This was continued until the observer had gone over a complete period of two alternations, then the $\sqrt{\text{mean}^2}$ readings of the primary and secondary E.M.F.'s and primary current were made. To do this required a period of time covering usually not more than two and one-half hours. Careful observations were made which showed that the insertion of one, two, or three lamps in the primary circuit *did not perceptibly change the relation* of the primary E.M.F. and current and secondary E.M.F. The indications of the ammeter gave data for correcting for variations of the speed of the dynamo.

Having arranged this apparatus, Prof. Ryan, assisted by Mr. Merritt, made a series of observations in the first place on a small Westinghouse 10-light transformer. The data and dimensions of the transformer are as below :—

Number of turns in the primary coil	675
„ „ „ secondary coil..................	35·
Resistance of the primary	21·8 ohms.
„ „ secondary	·04 „

Fig. 4 is a diagram furnished with a scale to which it was drawn, so that from it any details as to dimensions of the transformer can be obtained.

The iron discs of the magnetic circuit of the transformer were one-half millimetre in thickness, the insulating material between the iron discs being thin paper. The total volume of laminated iron used in the transformer was 2,050 cubic cms.

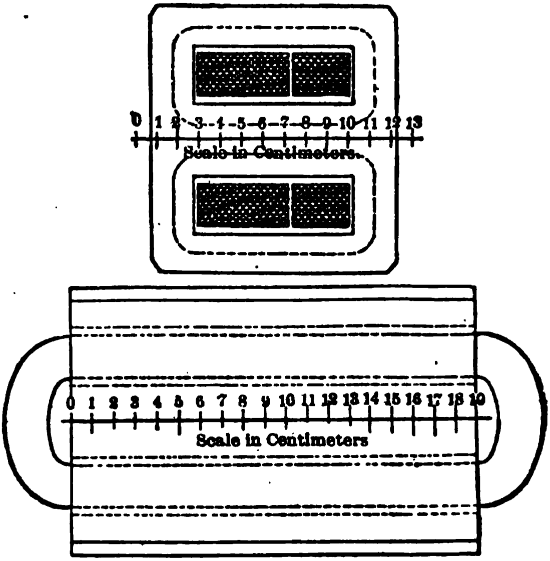

FIG. 4.—Section of 10-Light Westinghouse Transformer.

The mean cross-section of the magnetic circuit was 63·3 square cms., and the mean length of the magnetic circuit 30·8 cms.

The observations of the instantaneous values of the primary impressed electromotive force, the primary current, and the secondary electromotive force for various secondary loads on the transformer are given in the following tables and plotted to scale in the annexed diagrams :—

Secondary on Open Circuit.

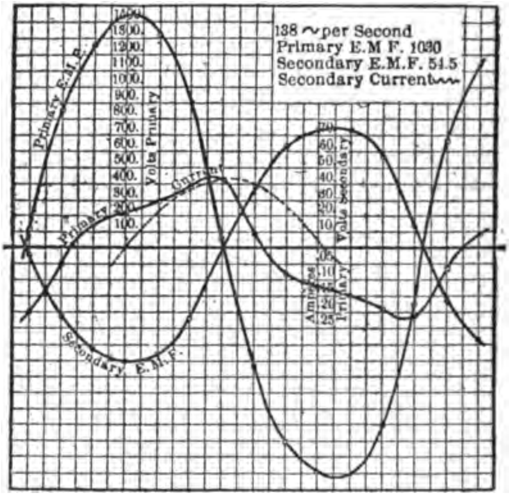

FIG. 5.—Transformer Diagram for Open Secondary Circuit.

Brush reading.	Primary E.M.F. volts.	Primary current. amperes.	Secondary E.M.F. volts.
21	119	·20	5·5
20	855	·05	62·7
19	1,250	·07	63·4
18	1,420	·11	70·7
17	1,330	·14	66·8
16	900	·19	46·0
15	45	·21	00·0
14	751	·04	37·8
13	1,210	·08	62·0
12	1,390	·12	72·0
11	1,410	·15	72·5
10	1,100	·18	57·8
9	355	·21	14·5
8	645	·08	32·3
7	1,130	·04	57·8
Observed $\sqrt{\text{mean}^2}$	1,025	·14	54·5
Calculated from curves $\sqrt{\text{mean}^2}$	1,030	·147	53·5

Secondary Closed through One Lamp.

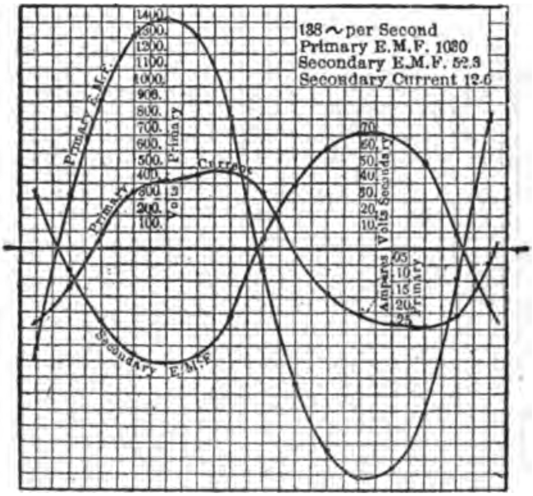

FIG. 6.—Transformer Diagram for a Secondary Current of 1·26 Amperes.

Brush reading.	Primary E.M.F. volts.	Primary current. amperes.	Secondary E.M.F. volts.
28	605	·225	31·4
27	330	·125	15·3
26	917	·048	45·2
25	1,300	·179	67·6
24	1,403	·215	71·7
23	1,300	·235	67·1
22	820	·239	43·8
21	132	·185	4·7
20	835	·000	3·9
19	1,238	·151	61·5
18	1,420	·215	71·7
17	1,363	·238	68·4
16	1,026	·246	52·7
15	170	·215	9·7
14	793	·048	35·6
Observed $\sqrt{\text{mean}^2}$	1,053	·196	52·3
Calculated from curves $\sqrt{\text{mean}^2}$	1,021	·190	51·4

Mean of ammeter readings, 1·26.

Secondary Closed through Five Lamps.

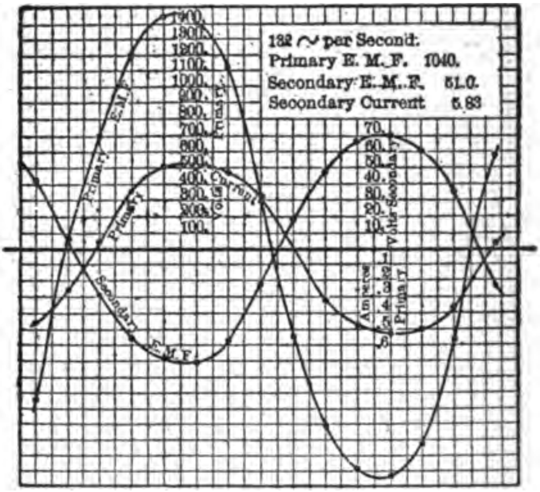

FIG. 7.—Transformer Diagram for a Secondary Current of 5·83 Amperes.

Brush reading.	Primary E.M.F. volts.	Primary current. amperes.	Secondary E.M.F. volts.
29	956	·449	40·3
28	41	·250	10·4
27	723	·000	28·9
26	1,194	·356	54·8
25	1,447	·495	69·1
24	1,350	·483	67·2
23	1,103	·453	57·6
22	293	·304	21·5
21	560	·000	19·8
20	1,110	·318	48·8
19	1,383	·464	65·7
18	1,429	·511	70·0
17	1,228	·500	60·3
16	567	·374	24·0
14·7	585	0·030	23·4
Observed $\sqrt{\text{mean}^2}$	1,050	·390	51·0
Calculated from curves $\sqrt{\text{mean}^2}$	1,036	·383	50·6

Mean ammeter reading, 5·83.

Secondary Closed through Ten Lamps.

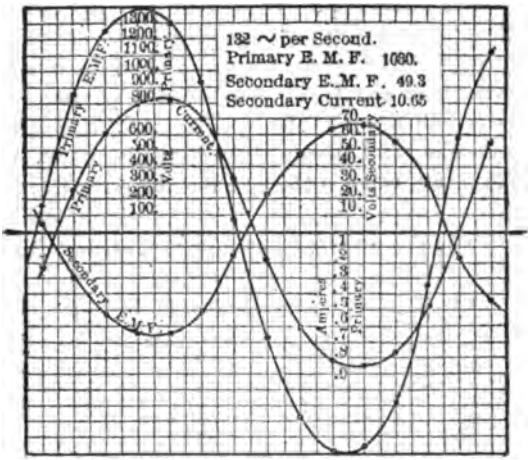

FIG. 8.—Transformer Diagram for a Secondary Current of 10·6 Amperes. (Full Load.)

Brush reading.	Primary E.M.F. volts.	Primary current. amperes.	Secondary E.M.F. volts.
21	138	·242	5·2
20	826	·276	29·7
19	1,237	·642	53·5
18	1,378	·795	64·0
17	1,300	·821	64·3
16	924	·700	51·1
15	63	·340	15·0
14	698	·188	23·7
13	1,138	·587	49·0
12	1,370	·810	63·7
11	1,343	·844	66·0
10	1,073	·771	26·5
9	323	·479	26·5
8	590	·000	17·0
7	1,117	·538	42·8
Observed $\sqrt{\text{mean}^2}$	1,040	·631	49·3
Calculated from curves $\sqrt{\text{mean}^2}$	1,020	·634	49·3

Mean ammeter reading, 10·65.

From these curves everything that it is desired to know about the transformer can be obtained. By multiplying together the corresponding instantaneous values of the primary current and E.M.F. the instantaneous value of the power given to the transformer can be obtained, and a curve of instantaneous watts laid down. The integration of this watt-curve will then give the total energy given to the transformer in the period. The same being performed for the secondary circuit, we have the means of obtaining the efficiency of the transformer at the various loads. Knowing the instantaneous values of the currents, we can also find the loss in the copper due to the current or the C^2R loss, and from the known total loss obtain the relative values of the losses in the iron and in the copper. In this way can be calculated the several losses and the percentage efficiency of transformation, which are as set down below for the transformer in question.

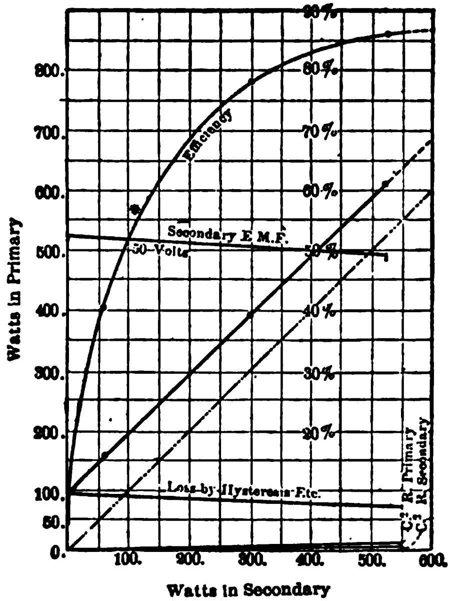

FIG. 9.—Efficiency Curves of 10-Light Westinghouse Transformer.

No. of lamps in secondary.	Pressure in volts at secondary terminals.	Power taken up in primary in watts.	Power given out in secondary in watts.	Efficiency of transformation.	Total power lost in watts.	Loss in the iron core in watts.	Loss in primary circuit in watts.	Loss in secondary circuit in watts.
None	52·3	96·1	0	0	96·1	95·7	·4	0
One	52·3	159·1	64·3	41·1%	94·8	93·9	·9	0
Five	51·6	388·6	300·9	77·5%	87·7	83·1	3·3	1·3
Ten	49	607·9	525·0	86·6%	82·9	69·7	8·7	4·8

The efficiency of this transformer at full load is seen to be only 86 per cent. This would amount to an "all day" efficiency of about 40 per cent.

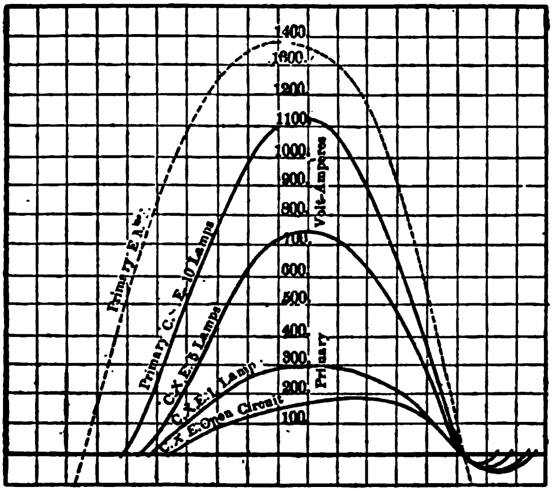

FIG. 10.—Power Curves of 10-Light Westinghouse Transformer.

The results of these observations are exhibited in the curves in Fig. 9. The power curves giving the power absorbed by the primary circuit for various lamp loads are given in Fig. 10.

These observations show clearly what are the nature of the energy losses in the transformer and the effects of the hysteresis of the iron.

We will next discuss some points which an examination of these curves suggest.

§ 2. Form and Disposition of the E.M.F. and Current Curves.—In the first place we may note that the curve of impressed primary electromotive force is in this case approximately a sine curve. Messrs. Ryan and Merritt subjected these observed curves to harmonic analysis. Whatever may be its form, the equation of the curve can in every case be expressed in accordance with Fourier's Theorem (*see* Vol. I., Chap. III., § 3) by a series of sine and cosine terms, and we can write the instantaneous value x of the current or E.M.F. as expressed by the series

$$x = A_0 + A_1 \sin pt + A_2 \sin 2pt + \text{etc.}$$
$$+ B_1 \cos pt + B_2 \cos 2pt + \text{etc.}$$

In which the constants A_n and B_n are determined by the equations

$$A_n = \frac{2}{T}\int_0^T x \sin \frac{2\pi n t}{T} dt,$$

; Use Joe's analyzer.

$$B_n = \frac{2}{T}\int_0^T x \cos \frac{2\pi n t}{T} dt.^*$$

Messrs. Ryan and Merritt determined the arithmetic values of these constants for all the observed curves. When the primary impressed E.M.F is thus analysed it is found that it can be expressed very nearly by four terms of the following Fourier series :—

$$E_1 = 1{,}500 \sin pt + 100 \sin 3pt - 42 \cos pt + 28 \cos 3pt.$$

Graphically it can be represented as in Fig. 11, where the dotted curves show the principal and secondary components of the original (firm line) curve. The primary E.M.F. is thus seen to be made up of a principal sine curve and a first harmonic of one-third the wave length. In the same way the secondary electromotive force was analysed and found to consist of a principal component and an harmonic of one-third the wave length (*see* Fig. 12). The expansion in harmonic terms for the secondary electromotive force being nearly

$$E_2 = -76{\cdot}2 \sin pt - 4{\cdot}8 \sin 3pt + 2{\cdot}7 \cos pt - 0{\cdot}1 \cos 3pt.$$

We shall not be far wrong in assuming that in all cases the curves of primary and secondary electromotive force are not

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[*] For the proof of this theorem the student is referred to Todhunter's "Integral Calculus," Chap. XIII. Also, Greenhill's "Integral Calculus," § 183.

very far removed from sine curves, and treating them accordingly. Doubt has been frequently thrown on this by some writers who have even ridiculed the assumption that the simple sine curve can express the form of the curve of electromotive force of any alternator; but strict investigation proves the assumption warrantable.

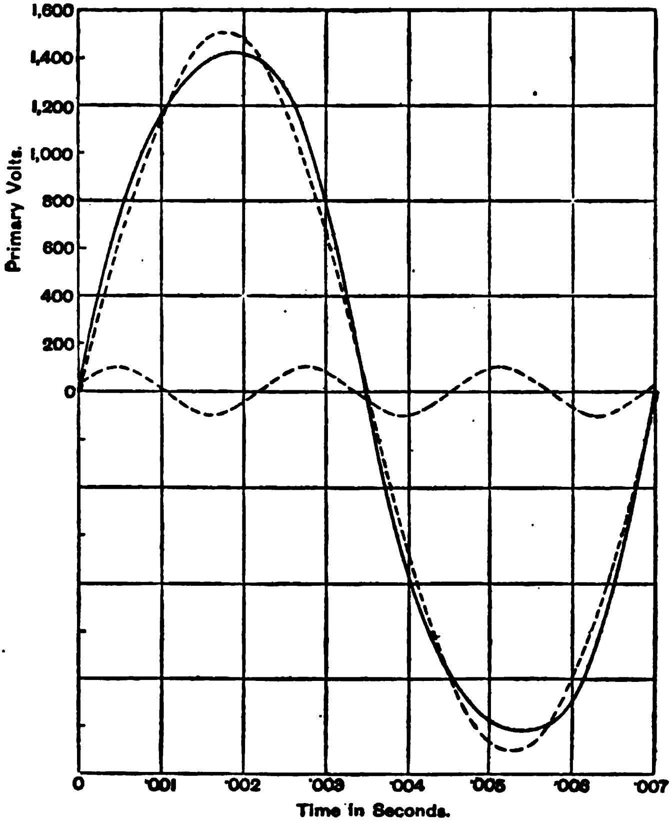

FIG. 11.—Harmonic Analysis of the Curve of Primary Electromotive Force of 10-Light Westinghouse Transformer. Dotted Curves represent the Harmonic Components.

Moreover, an inspection of the indicator diagrams shows us that the phases of the primary and secondary electromotive forces are exactly opposite to one another, or differ by 180deg., when there is no secondary load on the transformer, but that when there is a secondary load the secondary electromotive force is a very little in advance of the primary in phase.

It is quite different, however, with the primary current. We see by the eye, that when there is no secondary load the primary current curve is very far from being a simple sine curve. Messrs. Ryan and Merritt found that for the transformer they used the primary current curve could be analysed into three harmonic components (*see* Fig. 13), of which the wave lengths are respectively in the ratio, 1 : 3 : 5, and that it is expressible by the series,

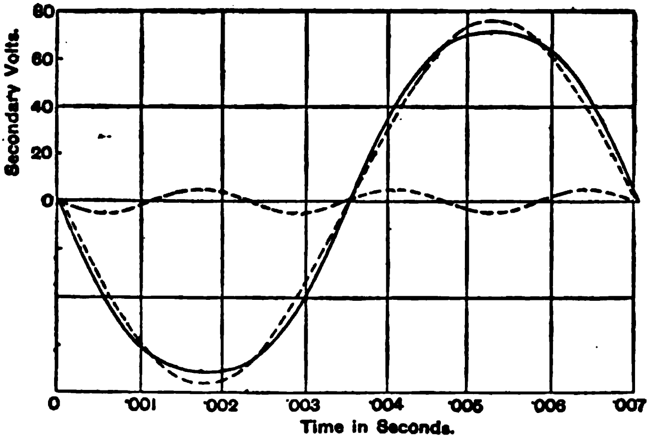

FIG. 12.—Harmonic Analysis of Curve of Secondary Electromotive Force of 10-Light Westinghouse Transformer.

$$i = 0{\cdot}129 \sin pt - 0{\cdot}148 \cos pt + {\cdot}011 \sin 3pt \\ - {\cdot}047 \cos 3pt - {\cdot}016 \cos 5pt.$$

If we inquire the cause of this distortion of the primary current the reply is that it is due to the hysteresis of the iron. If hysteresis were altogether absent the curve of primary current with open secondary would be a sine curve, lagging 90deg. behind the primary E.M.F. as represented by the dotted curve in Fig. 5. If eddy currents were set up in the core to any extent the effect of these would be to cause the primary current to be accelerated in phase or brought more into synchronism with the impressed E.M.F. If, in addition, hysteresis is present the result will be to make the current curve unsymmetrical in shape as we see it is. As the load on the transformer secondary circuit is increased the primary current curve is brought back more and more into synchronism with the primary impressed E.M.F., and in its final position it comes into almost exact opposition with the *secondary* electromotive force, losing its unsymmetrical form and approximating more to a simple sine

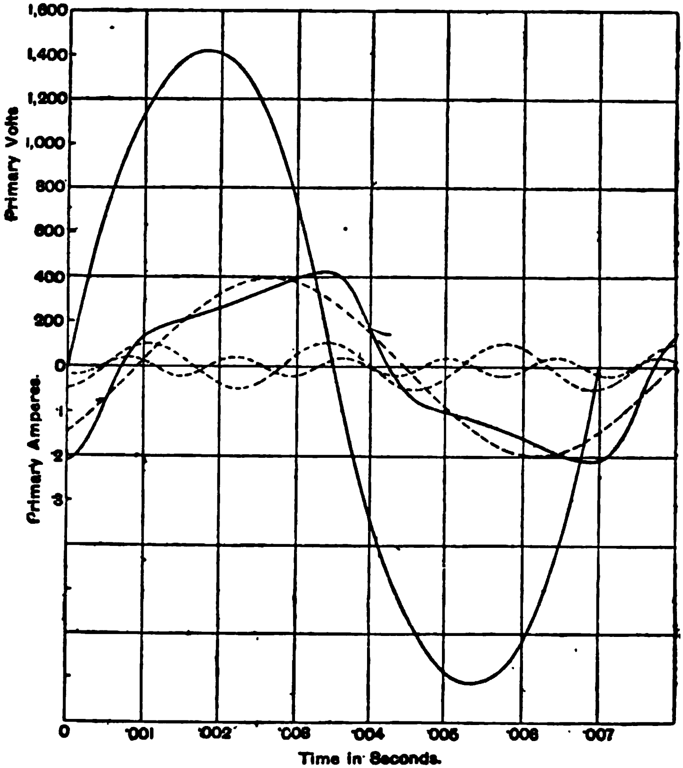

FIG. 13.—Harmonic Analysis of Curve of Primary Currents of the 10-Light Westinghouse Transformer on Open Secondary Circuit. The Curve of Primary Electromotive Force is also shown.

curve; and its harmonic analysis shows that as this loading up of the secondary circuit takes place the principal sine term of the Fourier series for the current becomes more important than the subsidiary terms.

When the transformer is fully loaded up on its secondary circuit we see that the secondary electromotive force lags a little behind the primary electromotive force, that is, it is not exactly opposite to it in phase. This is due chiefly to magnetic leakage. The primary current is under these circumstances almost exactly opposed in phase to the secondary electromotive force. Under conditions of full load none of the curves of electromotive force and current depart very widely from simple sine curves, and at any rate the sine curve form is sufficiently correct to allow of the application of simple analytical treatment in developing the theory of the transformer and in calculations. The marked exception to this is the primary current at low loads or the magnetising current.

Prof. Ryan and Mr. Merritt repeated the same kind of experiments with a 40-light Westinghouse transformer, and also with a transformer having a core made of iron wire; but the general results as to the form and relative phases of the current and E.M.F. curves were found to be of the same character as in the above experiments.

Messrs. Humphrey and Powell also studied, by this method, a 40-light Westinghouse transformer, and found the loss on open circuit to be only one-half that of the 10-light. Its efficiency at the full load was 96·2 per cent., equivalent to an all-day efficiency of 90 per cent. This improvement is due to the use of a better grade of iron.

§ 3. **Curves of Magnetic Induction and Leakage.**—The observed curves of current and electromotive force give us the means of determining other curves which will represent the variation of the magnetic induction in the core. The induction density is not necessarily and not generally the same in all parts of the core. If, at any instant, t, b_1 and b_2 represent the number of lines of force, commonly so called, which are linked with the primary and secondary circuits respectively, and if B_1 and B_2 are the maximum values of these quantities, then B_1 and B_2 are called the total inductions through the primary and secondary circuits. B_1 has not the same value as B_2 when the secondary circuit is loaded, because some lines of force which are linked with the primary circuit escape passing through the secondary, and this constitutes the magnetic leakage of the core. It is also generally the case that the induction density is not the same in all parts of the cross section of the core. Let B_1, B_2, however, be the maximum value of the lines *per square centimetre* of cross section of the core. If S is the area of cross section of the iron core or magnetic circuit, and if N_1 is the number of windings of the primary coil, then $N_1 S B_1$ will be the maximum total induction in C.G.S. units enclosed by the primary or will be the maximum of the total number of lines of force linked with the primary circuit. Let b_1 be as stated, the instantaneous value of B_1. Then $N_1 S \frac{d b_1}{d t}$ will express the time rate of change of b_1 at any instant, and will, therefore, be the back-electromotive force induced at that instant in the primary circuit. Hence, by the fundamental equation

$$N_1 S \frac{d b_1}{d t} + r \dot{i}_1 = e_1.$$

In which equation r stands for the ohmic resistance of the primary circuit, and i_1 and e_1 the instantaneous values of the primary current and impressed electromotive force at the same instant, when the secondary circuit is open. Therefore we have

$$\frac{d b_1}{d t} = \frac{e_1 - r \dot{i}_1}{N_1 S};$$

and therefore $b_1 = \int_{b_1 = o}^{b_1 = b_1} \frac{e_1 - r \dot{i}_1}{N_1 S} d t + \text{const.}$

where the integral is taken between proper limits. This equation shows us that if we have the curve for e_1 and the curve for i_1 we can construct a curve corresponding to $e_1 - r i_1$, and by integrating the area of this last curve between limits can obtain the value of the magnetic induction enclosed by the primary circuit at the instant corresponding to any value of e_1 and i_1. It is obvious that when $r i_1 = e_1$ then $\frac{d b_1}{d t} = o$, and hence this point corresponds to the maximum positive or negative value of the induction B_1.

Again, if B_2 stands for the maximum value of the magnetic induction within the secondary circuit, or for the maximum number of lines of force per square centimetre, which are linked with the secondary circuit, and if b_2 stands for the instantaneous value of the same, then the instantaneous value of the secondary electromotive force e_2 is

$$e_2 = N_2 S \frac{d b_2}{d t}.$$

Where N_2 is the number of secondary windings and S the cross section of the magnetic circuit, it follows that

$$b_2 = \int \frac{e_2}{N_2 S} d t + \text{const.}$$

And the instantaneous value of the induction through the secondary circuit at any instant can be obtained by integrating the curve of secondary electromotive force between proper limits (see Fig. 14). In general b_1 is not identical with b_2, and the curves of induction so formed are not similar. This is because magnetic leakage intervenes to cause the induction through the secondary circuit to be less than the induction through the primary circuit, that is to say, all the lines of force which are linked with the primary are not linked with the secondary circuit. The difference between b_1 and b_2 being taken, gives us the curve of magnetic leakage. In Fig. 15 the curve F, representing b_1, is so deduced from the primary electromotive force, and the curve G, representing b_2, is deduced from the curve of secondary electromotive force. The curve H represents the curve of magnetic leakage. The ordinates of the curve H are obtained by taking the difference of those of curves F and G.

The student will find it an assistance to adopt a suggestion which has already been made of giving a name to a unit of magnetic induction equal to 10^8 "lines of magnetic force." This quantity it has been proposed to call *one gauss*. The gauss, therefore, is a unit in which magnetic induction is measured. The common custom which we have hitherto followed is to employ the term *the magnetic induction* to denote that which ought properly to be called *the density of magnetic induction*.

This necessitates the use of the phrase *total induction*, to denote the whole number of so-called lines of force passing through any area and to distinguish it from the number passing through a unit of area taken perpendicularly to those lines. The simplest plan is to adopt the word *gauss* as the name for a certain amount of magnetic induction or for 10^8 lines of magnetic force. We can then speak of an induction, meaning

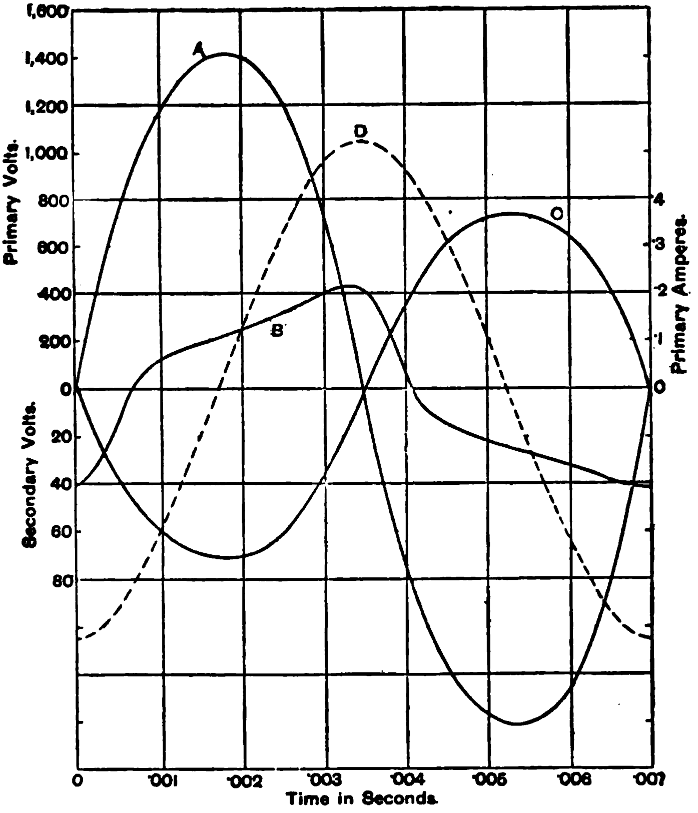

FIG. 14.—The Dotted Curve D is the Curve of Total Magnetic Induction in the Core of the 10-Light Westinghouse Transformer calculated from the Curves of Primary Electromotive Force (A) and Current (B). One scale division (vertical) = 100,000 Lines (C.G.S.) = ·001 Gauss.

a total induction of so many *gausses*, through any area, and, if we wish to refer to the induction density, or *the* induction, at any point, we can do so by speaking of the *gausses* per square

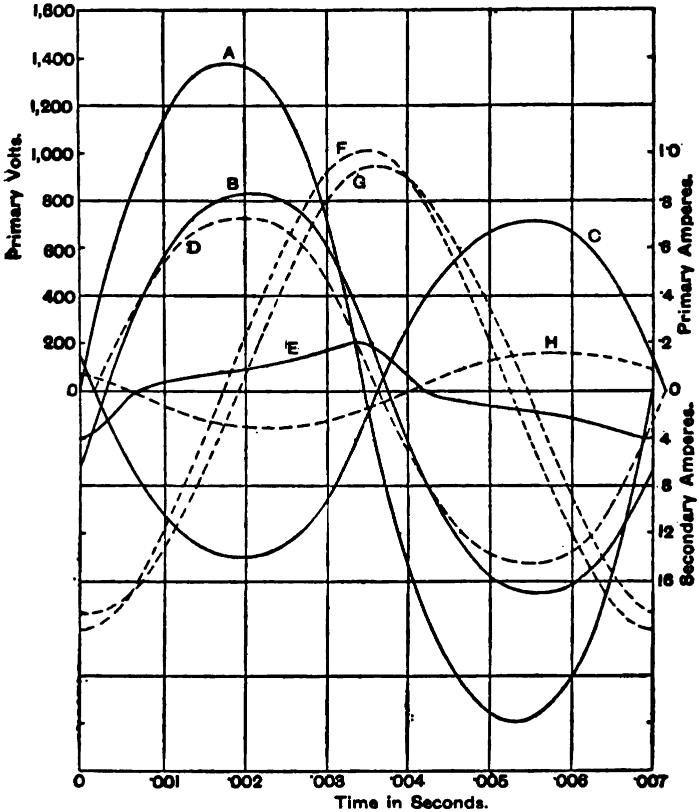

FIG. 15.—Transformer Diagram for 10-Light Westinghouse Transformer. A = Primary E.M.F.; B = Primary Current; F = Induction through Primary; G = Induction through Secondary; H = Magnetic Leakage Curve; E = Magnetising Component of Primary; C = Secondary Current.

centimetre at that point. In the above equations if *e* and *i* are measured in volts and amperes, *b* is determined in gausses, and can always be converted to C.-G.-S. measure by multiplication by 10^8.

From the induction curves so obtained, Prof. Ryan was able to draw the hysteresis diagram for the transformer. If we set off as horizontal abscissæ the values of the primary magnetising current and as ordinates the corresponding total magnetic induction through the primary circuit, the result is seen in Fig. 16 for the small 10-light Westinghouse transformer. On open circuit the maximum induction density in the iron was 3,850 lines per square centimetre. The iron discs of which the magnetic circuit of this transformer was composed were one half millimetre in thickness, and separated by paper. The total volume of laminated iron was 2,050 cubic centimetres. The mean cross-section of the magnetic circuit was 63·3 square centimetres, and the mean length of the magnetic circuit was

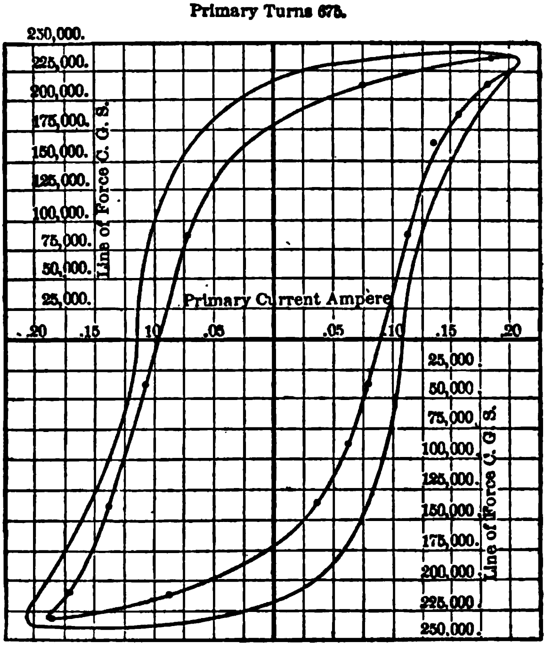

FIG. 16.—Energy-loss Diagram for 10-Light Westinghouse Transformer. Outer Curve is the (B, *i*) Curve ; inner Curve the Static Hysteresis Curve. Horizontal abscissæ represent Magnetising Current ; Vertical Ordinates total Induction in Core in C.G.S. Units.

30·8 centimetres. Hence, the maximum value of the total induction through the cross-section of the magnetic circuit was about 240,000 lines; and since the primary turns were 675 in number, the maximum total linkage of lines with the primary circuit, at maximum induction, would be $675 \times 3850 \times 63{\cdot}3 = 1{\cdot}652 \times 10^8$ nearly, or about 1·65 gausses. If we integrate the area of the outer loop in Fig. 16 in terms of a rectangular unit of area one of whose sides represents *one* ampere to the same scale as the abscissæ, and the other side *one gauss* on the same scale on which the vertical ordinates are taken, we find the area of this loop to be very nearly ·001 of such unit. Multiplying this by 675, or the number of primary turns, we have the number 0·67, which is the loss of energy in the core for one complete cycle measured in *joules*. For, if we take the fundamental equation referred to just above, viz.—

$$N_1 S \frac{d b_1}{d t} + r i_1 = e_1$$

and multiply all through by i_1 and $d t$, we have

$$N_1 S i_1 d b_1 + r i_1^2 d t = e_1 i_1 d t.$$

Assume these quantities all to be measured in C.-G.-S. units, then the right-hand term represents the energy given to the primary circuit of the transformer in the short time, $d t$; the middle term represents the loss in the copper or the resistance loss; and the left-hand term must therefore represent the loss in the iron in the same short time. If we integrate all these terms through one complete period, then the integral of $N_1 S i_1 d b_1$ taken through a complete period is represented by the area of the closed curve in Fig. 16, of which ordinates represent the various values of $S b_1$ or the total induction and abscissæ the values of i_1 or the magnetising current. Hence, when i_1 is measured in amperes and $S b_1$ in *gausses*, the product of the area, and the primary turns, N_1, gives us the energy lost in the core in one cycle in *joules*. If there are 138 cycles per second, then the total loss in the core per second is $\cdot 67 \times 138 = 92{\cdot}46$; and this represents the total loss in watts in the core on open circuit. Hence, since the volume of the core is nearly 2,000 cubic centimetres, the loss per cubic centimetre is ·046 of a watt. The total observed loss in the core is 95·7 watts, eddy current loss and hysteresis being both included.

It was thought that it would be interesting to see how far the diagram of total iron loss so obtained agreed with that obtained by the method of Ewing when the iron was carried through its magnetic cycle slowly. Accordingly, Mr. Merritt determined the inner curve shown in Fig. 16 by that method. The iron was not taken quite up to the same maximum of magnetisation in both cases, and hence the agreements of the two curves is not very close; but as they stand they seem to show that the hysteresis is not increased by carrying the iron through its magnetic cycle more rapidly. On the other hand, there is, apparently, a marked decrease in the total loss of energy in the iron as the transformer is gradually loaded up. The iron losses of the transformer seem to decrease as secondary current increases.

This fact, which is indicated by Prof. Ryan's experiments, seems to be confirmed also by those of other experimentalists. As far back as 1888, some experiments of Prof. Ayrton's on a small Kapp and Snell transformer indicated that this result might be looked upon as probable. In 1890 Prof. Roiti, of Florence, carried out a very valuable series of experiments* on a Zipernowsky-Deri transformer, in which, after giving the results of his measurements, he says, "We are apparently thus led to a deduction of considerable theoretical importance, and which would be opposed to the generally accepted opinion of the present day relatively to the hysteresis of iron, and that is that the energy wasted on the reversals of magnetism seems to be negligible. He goes on to point out that the numerical results obtained for the energy dissipated in iron when it is carried *slowly* through a cycle of magnetism, as in the experiments of Ewing and Hopkinson, cannot in his opinion be applied to magnetic operations in which the iron is carried through its magnetic cycle one or two hundred times in a second.

Prof. Ayrton and Mr. Taylor, in a Paper read before the Physical Society of London† in 1891, arrive at the same conclusion; and Mr. Mordey at the same time made known figures which he had obtained supporting that view. In a discussion at the Institution of Electrical Engineers‡ Mr. Mordey gave the actual measurements made with a 6,000 watt-transformer. On open secondary circuit the loss in the transformer was 110 watts; at full load the loss was 205 watts; the loss in the copper was found to be 176 watts at full load. Hence we have the loss in the iron at full load as 29 watts. The magnetic induction was about 4,000 C.-G.-S. These results of Mr. Mordey for the transformer in question are quite inconsistent with the results given by Prof. Ewing for static hysteresis or for the loss at corresponding inductions when the cycle is traversed slowly.* The general tendency of all these experiments, if correct, would be to show that we cannot calculate the losses in a transformer on the assumption that the iron losses are constant at all loads and equal to the slow-cycle values when the frequency of reversal is between 100 and 200 ∿ per second. Calculations based on this assumption may, or may not, be erroneous, but we are left with the conclusion that the losses in the iron of a transformer can only properly be determined by experiment. It cannot be said yet that the subject is exhausted, for the reason has yet to be determined of this remarkable reduction in the hysteresis waste at full load. It has been suggested that the mechanical vibration of the iron at full load diminishes the hysteresis. If we can trust to mechanical analogies we should expect the hysteresis to diminish when the frequency is increased. Every material exhibits strain hysteresis when slowly loaded or unloaded, but exhibits no hysteresis when the change of stress is very rapid. Thus it has been pointed out that the most inelastic of bodies, such as pitch, transmits a musical note unchanged; and, trusting to this analogy, some physicists have maintained that magnetic hysteresis must be negligible when the magnetic cycle is rapidly performed. Others doubt this; and we find thus a difference of opinion existing on an important matter.

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* See *The Electrician*, Vol. XXVI., p. 540.

† See *La Lumière Electrique*, Vol. XXXV., 1890, pp. 479—525.

‡ *Journal* of Institution of Electrical Engineers, Vol. XX., April, 1891 p. 207.

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* Mr. Mordey quoted also (*loc. cit.*) a letter from Prof. Ewing, in which he expressed the opinion that the loss from hysteresis is not proved to be proportional to the speed of magnetic reversals, especially when that speed is high. This opinion modifies the view previously expressed by the same writer (see *Phil. Trans.*, 1885, p. 554, and *The Electrician*, Vol. XXV., 1890, p. 169), that the loss would probably be greater at high rates of reversal than at low.

The above conclusions that the iron losses in a transformer decrease as the load on the secondary is increased cannot be said, however, to have been generally accepted, and many felt that the subject required further investigation. This it has received from Prof. Ewing, who attacked the problem directly in an ingenious manner.* His experiments were as follows:—Two precisely similar model transformers were wound, the core consisting in each case of a ring of *insulated* iron wire, over which was wound, on each ring, two equal primaries and two equal secondaries. The primaries of one transformer were wound so as to oppose each other, and the secondaries of the same transformer were also wound so as to oppose each other. The result was that this transformer was magnetically inactive whatever current was passed through its primary or secondary. The two transformers had the circuits connected in series, the same alternating primary current traversing both primaries. The secondary circuits were also joined in series. Hence the primary and secondary circuits of both were traversed by the same currents, and, therefore, had produced in them frictional heat due to ohmic resistance at the same rate. The iron core of one transformer was, however, not magnetised by the currents, whilst that of the other one was magnetised. Hence the core of the active transformer got hotter than that of the other. The core of the magnetically inactive transformer was then brought up to the same temperature as that of the active one by passing a continuous current through the circuit of insulated iron wire forming its core, and equality of temperature obtained as tested by means of a pair of thermoelectric junctions buried in both cores.

By means of a "tertiary" coil on the active transformer equality in the magnetic induction of its core was also preserved. The experiment consisted in working the transformers at constant induction in the core of the active one, but first on open secondary and then on closed secondary circuit, and noting whether the heat required to be given to the core of the magnetically inactive transformer to balance its core temperature with that of the other remained the same in the two cases. No difference in any case could be found in the continuous current required to balance the temperatures of the cores. The inference is that the loss through hysteresis and eddy currents went on in the magnetised core at *the same rate*, whether the secondary circuit was loaded, or whether it was on open circuit. As far as these experiments have gone at the time of writing, the issue seems pretty clear that the iron losses in a transformer core are constant at all loads, at least as far as regards pure magnetic hysteresis.

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* See *The Electrician*, Vol. XXVIII., p. 111, December 4, 1891.

§ 4. Other Methods of Obtaining Transformer Diagrams and Current Curves.—Dr. Louis Duncan, of Johns Hopkins University, has suggested an elegant method of obtaining the curves of current and E.M.F. of a transformer or alternator simultaneously without the special difficulties attendant on the determinations made as above described. Four small dynamometers are constructed, of which the fixed coils are wound with wire of such size and length as to be suitable for insertion in and across the primary circuit and in and across the secondary circuit of the transformer to be tested. The movable coils of these dynamometers are all joined up in series, and arranged so as to be traversed by a continuous cur

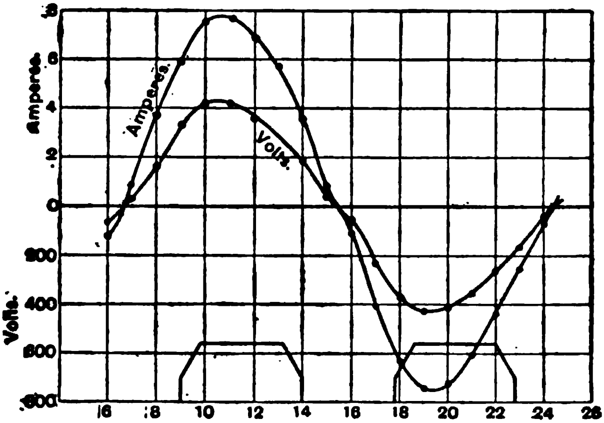

FIG. 17.—Electromotive Force and Current Curves of Stanley Arc Light Alternator when working on a Load of five Incandescent Lamps. The positions of the Pole Pieces are shown at the bottom of the Diagram.

rent from a few cells of a secondary battery. The circuit of these cells is interrupted by a pin fixed to the armature shaft, which touches an insulated wiper or spring, suitably placed, and which wiper can be shifted into various angular positions, so as to make contact at various equidistant intervals of time right through a complete phase of the armature E.M.F. period. It is evident that each dynamometer when traversed by the alternating and interrupted currents will experience a rapid series of impulses which in each case will be proportional to the instantaneous magnitude of the current passing through its fixed coil during the short period in which the wiper is making contact. These impulses run together into a continuous torque on the movable coil, which can be measured in the usual way by a twist on the supporting spring or wire. Hence we have here an arrangement which possesses the great advantage that all four curves can be determined at once, and also that the current through the contact-breaker can be made to be a relatively small current of small E.M.F. By employing a galvanometer in series with the moveable coils, we can correct for any error due to change in strength of the battery current. The method can easily be modified so as to photograph all the four curves in proper relative position.

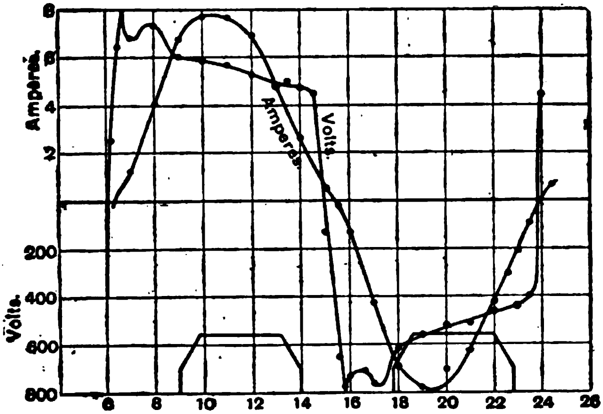

FIG. 18.—Electromotive Force and Current Curves of Stanley Alternator when working on a Load of 10 Arc Lamps.

M. Blondlot has also devised a method by which a condenser is connected for an instant at some period of the E.M.F. phase to the armature terminals by means of a revolving contact pin and wiper, and is then discharged through a galvanometer. By this means a rapid series of discharges are sent through the galvanometer, and the instantaneous value of the E.M.F. of the alternator thus becomes known. Other experimentalists have devised modifications of this method, and, by using a set of two or more contact pins and wipers on the revolving alternator shaft several curves of current or E.M.F. can be determined at one time. By employing one or other of these methods different observers have made a special study of the forms of the current and electromotive curves of alternators and transformers when supplying inductive and non-inductive circuits. Space will not allow us to enter into a full discussion of the various forms presented by the E.M.F. curve of different species of alternator. For the case of a single practically non-inductive loop revolving round an axis in its own plane in a uniform magnetic field it is

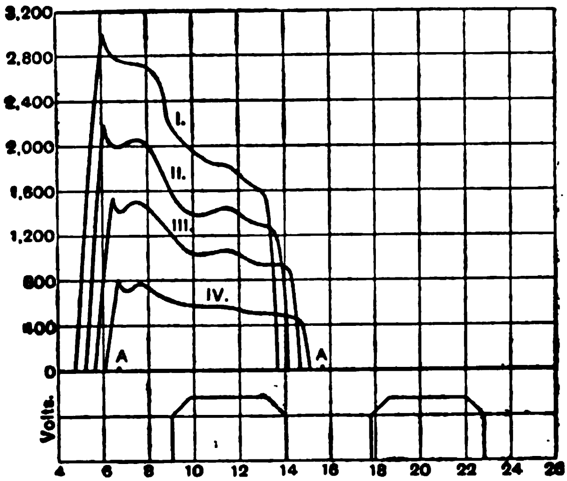

FIG. 19.—Electromotive Force Curves of Stanley Alternator for varying numbers of Arc Lamps. I., 40 Lamps; II., 30 Lamps; III., 20 Lamps; IV. 10 Lamps; A A, zero at short circuit.

clear that the simple sine curve represents the form of this curve of varying E.M.F. For many kinds of alternators it would appear that the form of the E.M.F. curve is not widely different from the simple sine curve. The form *may*, however, be greatly varied, depending upon the geometrical form of the field poles, upon whether the armature has an iron core, and if so of what kind, and upon the nature of the external circuit. Experiment shows that great deviations from a simple sine curve may take place. This is not always due to the internal actions in the machine. Thus, in the case of the Stanley or Westinghouse arc light alternators, which we have described in § 17 of Chapter II., very peculiar variations in the E.M.F. curve were found to be dependent upon the nature of the external circuit.

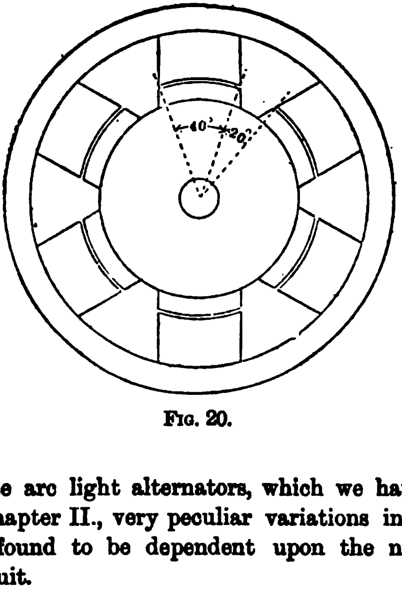

FIG. 20.

These experiments were made by Messrs. Tobey and Walbridge,* at the Cornell University Electrical Laboratories. When this Stanley alternator was worked on short circuit, or on a load of incandescent lamps, the E.M.F. curve of the machine was not very different from a simple sine curve (*see* Fig. 17). When the machine was worked on arc lamps in series, as described in a former chapter, the form of the E.M.F. curve was totally altered, and it assumed the curious peaked form shown in Figs. 18 and 19. At the same time, the position of the armature with respect to the field poles for zero E.M.F. was changed. The explanation advanced by the investigators to explain this curious change in form of the E.M.F. curve is that when working on alternating arcs the stoppage of the arc at each reversal of current in it is accompanied by a great rise in resistance of the circuit, and that the E.M.F. required to begin the arc again is much greater than that required to maintain it. The current curves of the machine are in all cases much more nearly sinoidal in form. In a discussion which followed the reading of the Paper describing these experiments, Dr. Pupin made the remark that the variation of the E.M.F. was probably due to the variation of resistance of the arcs with current. Since in the arc the greater the current the less is the resistance, the varying resistance of the arcs

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* See *Electrical World* of New York, November 8, 1890, Vol. XVI., p. 339.

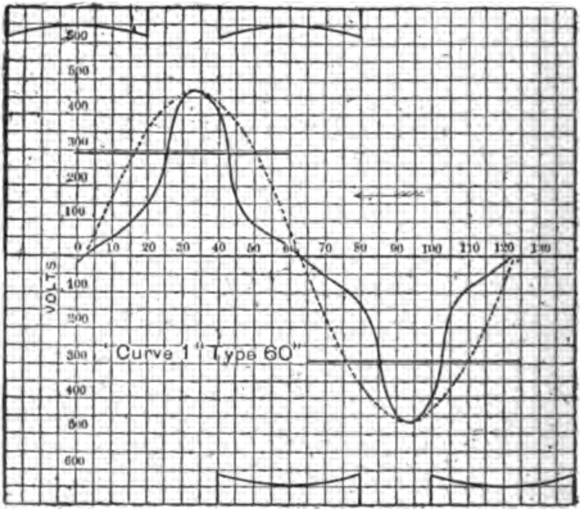

FIG. 21.—Electromotive Force Curve (firm line) on Open Circuit of Alternator represented in Fig. 20. The dotted curve is a Sine Curve.

would, in a machine so responsive as this alternator, call forth a greater E.M.F. at the beginning of the period. The results, however, show that it does not do to assume without warrant that the E.M.F. curve of any given machine has a fixed form independent of the load. Neither must it be assumed without proof that for any given machine the form of the E.M.F. curve is sinoidal, even when working on a non-inductive load. Mr. Warren B. Lewis has studied* the E.M.F. curves of a form of alternator not unlike the Ganz alternator in the form of its iron circuit (*see* Fig. 20), except that the revolving portion is the armature; and the result of this study is to show that the E.M.F. curve of this alternator on open circuit has the form shown in Fig. 21. The dotted line is a sine curve, drawn for comparison. The positions of the field poles are also shown in the diagrams. When worked on a water resistance absorbing

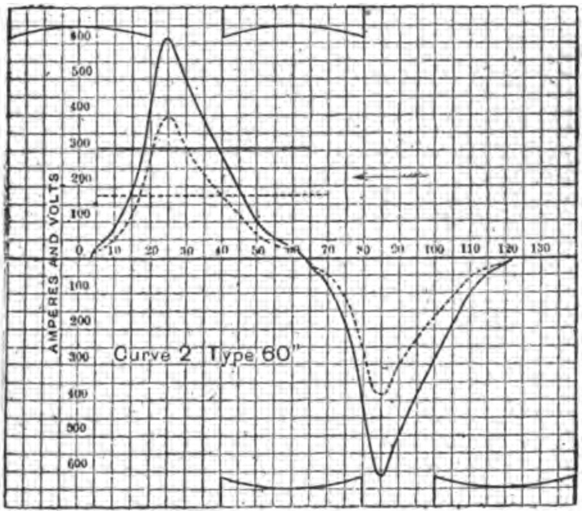

Fig. 22.—Electromotive Force Curve (firm line) of Alternator shown in Fig. 20 when working on a Water-resistance Load. The dotted curve is the Current Curve.

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[*] See *Electrical World* of New York, 1891; also *Electrician*, Vol. XXVIII., p. 90, 1891.

52 kilowatts the form of the E.M.F. is quite altered. The maximum output of the machine was 60 kilowatts. Fig. 22 shows this last E.M.F. curve, and the dotted curve is the current curve. When worked on an inductive load the curves of current and E.M.F. were again quite altered (*see* Fig. 23). In this diagram we see distinctly the "lag" of the current due to the inductance of the circuit, and also the way in which the inductance of the circuit smooths out the ripples on the E.M.F. curve, and gives a current curve not very far from sinoidal.

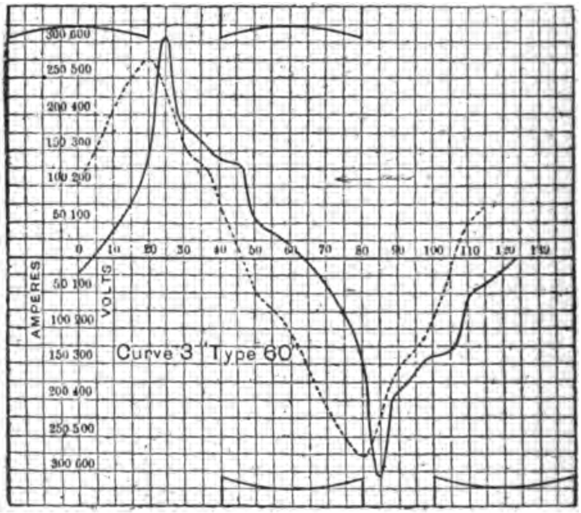

Fig. 23.—Electromotive Force (firm line) Curve, and Current Curve (dotted) of Alternator shown in Fig. 20, when working on Inductive Resistance.

For an alternator with a field and armature not unlike a Siemens alternator, Mr. Lewis found an E.M.F. curve very closely sinoidal in form (*see* Fig. 24).

Dr. O. Frölich has worked out a very ingenious form of apparatus, by means of which a more or less approximate optical reproduction of the form of a current curve can be obtained and viewed at one glance. The principle of the apparatus is as follows:—A ray of light from an electric lamp is focussed by means of lenses, and reflected from a small silvered mirror which is affixed to a telephone diaphragm eccentrically—that is, somewhere between the centre and the edge of the diaphragm. The ray is reflected back on to a revolving cylinder covered with vertical facets of silvered glass, and thence on to a screen, forming a spot of light. If a periodic current is sent through the telephone, it causes the diaphragm to bulge in and out, and displaces the small mirror on it angularly, and thus deflects the ray of light up or down.

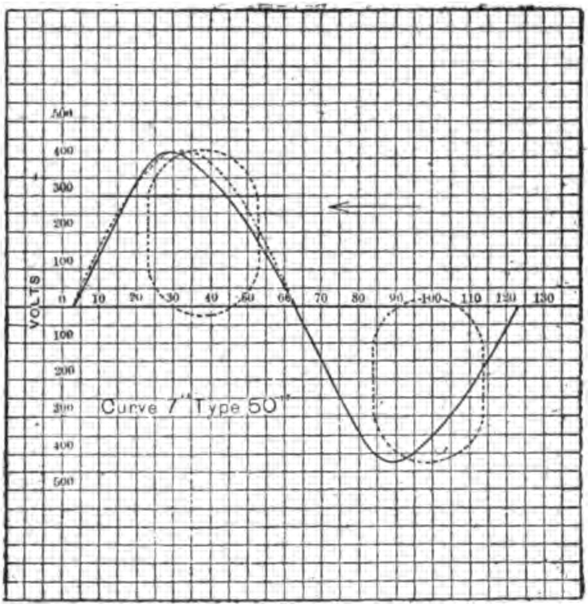

FIG. 24.—Electromotive Force Curve of Alternator of Siemens Type.

If the polygonal mirror rotates on an axis lying in the plane of the displacement of this ray, and if, moreover, its speed of rotation is so controlled that it revolves through such an angle during each vibration of the diaphragm as will suffice to bring each revolving facet of its surface successively to be the reflecting surface for the ray, then a stationary optical wave is formed by the rapidly-moving spot of light. Hence, apart from oscillations due to the natural period of oscillations of the diaphragm, and assuming that the telephone diaphragm vibrates in extent and manner so as to imitate exactly the changes of current strength in its coils, we get an optical reproduction of the form of the periodic current sent through the telephone. If, for instance, a constant E.M.F. from a battery is applied through an inductive resistance, and then removed, we get the current curve, shown in Fig. 25, reproduced upon the screen. This shows the gradual rise of current strength, and retardation due to inductance. The ripples on the curve are merely disturbances produced by the natural period of vibration of the diaphragm.

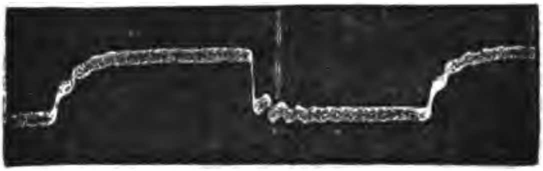

FIG. 25.

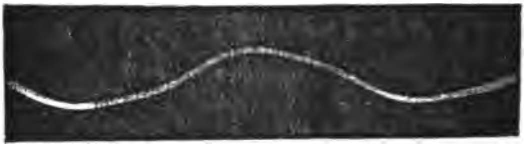

FIG. 26.

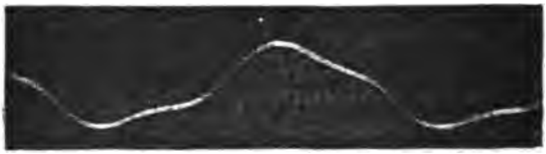

FIG. 27.

The curve in Fig. 26 was obtained by passing the current from a small Siemens alternator through the telephone. In this case the armature possessed no iron core. With an iron-cored armature the current curve was as shown in Fig. 27, in which distortion and change of form from a simple sine curve is seen. Fig. 28 shows curves obtained with and without self-induction in the circuit of the alternator. This optical method of reproducing periodic current curves was exhibited first at the Frankfort Electrical Exhibition of 1891 (see *The Electrician*, Vol. XXVIII., p. 60), and may be probably developed into a very useful and important method of investigation.

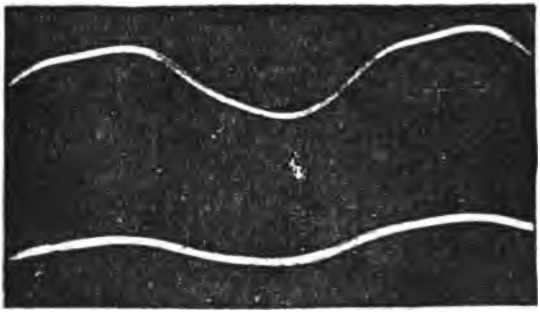

FIG. 28.

§ 5. Discussion of the Transformer Diagrams.—Referring to the indicator diagrams of the small Westinghouse transformer in preceding sections, we see that the following inferences are deducible from them, considering them as typical :—

(i.) The curve of primary impressed E.M.F. is here, at any rate approximately, a simple periodic curve.

(ii.) When the transformer has its secondary circuit open, the curve of secondary E.M.F. is exactly opposed to in phase, or differs in phase by 180deg. from the primary E.M.F., and is also approximately sinoidal.

(iii.) The curve of magnetic induction lags behind the curve of impressed primary E.M.F. by about 90deg., or a quarter of a wave length. We may here note that the *lag* of the curves relatively to one another must be measured by the relative position of the zero points of the curves or positions at which the curves cut the horizontal line or axis of time. The curve of induction for open secondary circuit is not, and cannot be, a simple sine curve, because otherwise it would follow that the curve of primary current in open secondary circuit would be a simple periodic curve also, but it is not so.

(iv.) The curve of primary current for open secondary circuit, or the magnetising current commonly so called, is always an irregular and unsymmetrical curve. If the magnetisation is carried up over the "knee" of the magnetising curve the current curve may run up into a sharp peak, as in Fig. 29.

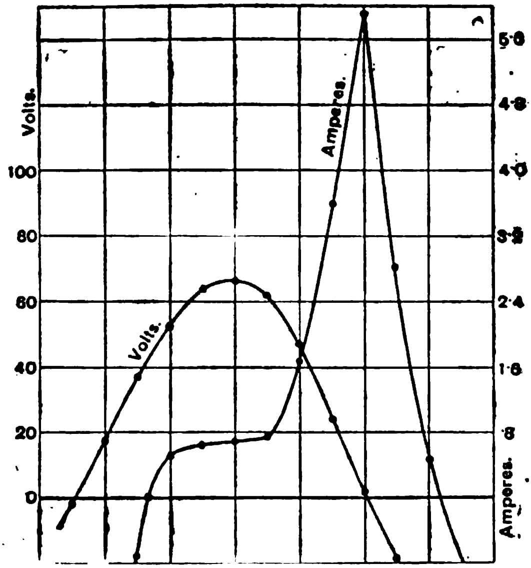

FIG. 29.—The Electromotive Force Curve, and the Current Curve of the Primary Circuit (open secondary) of a Transformer, when the Magnetisation is carried up over the "Knee" of the Magnetisation Curve. ∿ = 92.

As the load on the secondary circuit is increased this irregularity decreases, and the curve of primary current at full load approximates to a simple periodic curve. As the secondary current increases the primary current is brought forward more into synchronism with the primary E.M.F., but never quite gets into step with it. At the same time, the secondary E.M.F. curve lags a little as the secondary load increases, because the phase of the induction through the secondary is delayed behind that through the primary by reason of the magnetic leakage out of the core. In the limit, at full load the primary current comes into almost exact opposition to the secondary E.M.F. (*see* Figs. 30 and 31), and hence when the secondary circuit is approximately non-inductive into almost exact opposition as regards phase to the secondary current.

(v.) The magnetic leakage exercises a disturbing effect upon the shape of the curve of secondary E.M.F., making it unsymmetrical in shape.

This is well shown by some further experiments of Prof. H. J. Ryan,* in which a small ring core transformer was purposely badly designed, the secondary being wound all on one side, and the primary all on the other, and the resulting magnetic leakage makes itself evident in the curves as shown in Figs. 30 and 31, in the lagging and distortion of the curve of secondary E.M.F. This transformer exhibited in an exaggerated form the defects present in most commercial transformers. Further experiments by Mr. L. B. Marks, with this model transformer in the Cornell University Laboratory, are very instructive. The iron core consisted of nine well-rusted iron rings 1·1 centimetres in cross section diameter, and of a mean diameter across the ring of 17 centimetres. The primary circuit wound on this core consisted of 500 turns of bare copper wire, No. 18, insulated with asbestos paper. The primary circuit resistance was 1·65 ohms. The secondary circuit had 155 turns and a resistance of 0·71 ohm. The maximum induction density was not raised above 3,000 C.-G.-S. (lines per square centimetre) in these experiments.

Figs. 30 and 31 show the diagrams taken with open secondary circuit, and with secondary circuit closed so as to create a secondary current. The secondary E.M.F. curve is seen to become more symmetrical under load, but at the same time its maximum ordinate diminishes. So that whilst the ratio of the turns of primary to secondary turns in this transformer was 3:2, the ratio of primary to secondary E.M.F. varied between no load and full load from 4 : 1 to 8 : 1. This shows clearly that it is only in transformers with negligible magnetic leakage and in which the whole of the induction through the primary

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* *Electrical Review of* New York, Vol. XVI., p. 9, July 5, 1890.

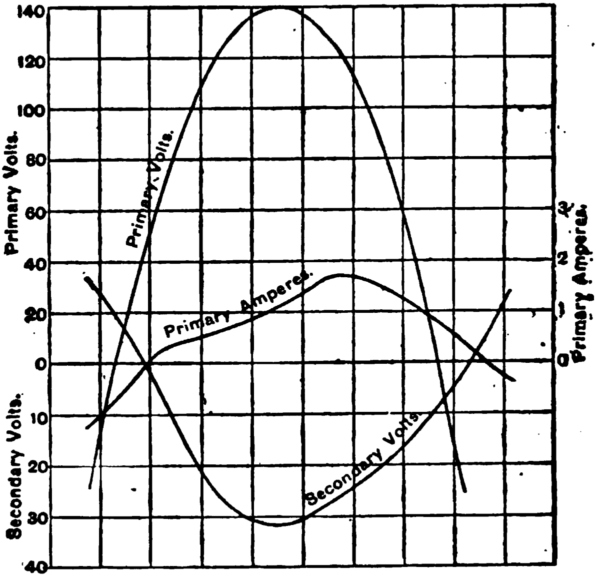

FIG. 30.—Electromotive Force Curve, and Current Curve of badly designed Ring Core Transformer with much Magnetic Leakage, showing the Distortion of the Secondary Electromotive Force Curve. Open Secondary Circuit.

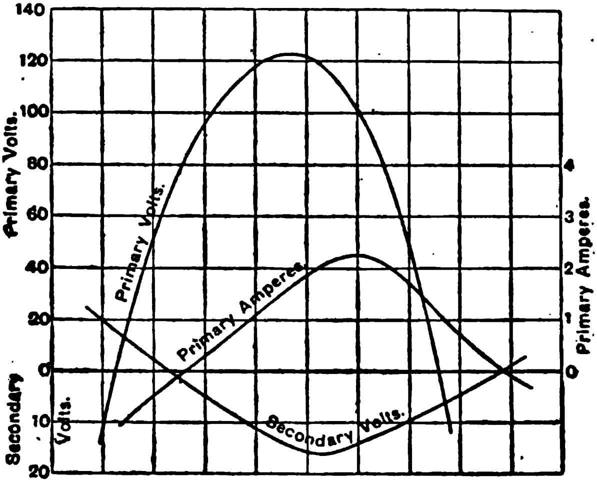

FIG. 31.—Diagrams of the same Transformer with Magnetic Leakage. Secondary Electromotive Force Curve less distorted. In this case the Secondary Circuit was closed and full current sent.

traverses the secondary, that we can assume the primary and secondary E.M.F.s are in the ratio of the number of the convolutions of the circuits.

§ 6. Experiments on the Iron Core Losses.—Mr. Marks also made experiments with this same model transformer when raised to different temperatures, and from these experiments deduced the following table of results :—

Primary volts ($\sqrt{\text{mean}^2}$) = 90.

The temperature of the transformer core.	The loss in the core, or the iron-loss, in watts.	Power given to primary circuit in watts.	Power given out by the secondary circuit in watts.
97°·5C.	122	122	0
300°C.	72	72	0
270°C.	79	79	0
99°C.	117	141	24
270°C.	80	116	36

This table is to be understood as follows :—When the secondary circuit was open, the primary took up 122 watts, and the core came to a temperature of 97°·5C. due to hysteresis and eddy currents. On raising the core by external heat to 300°C. it was found that the energy absorbed by the primary circuit diminished to 72 watts. Furthermore, it is seen that loss in the core is practically independent of the secondary output. These figures indicate that the loss is largely due to eddy currents, and that rise of temperature by decreasing the electrical conductivity of the iron, decreases the loss due to the eddy currents. By experiments on a cast-iron ring made in the Cornell University laboratory, Mr. A. Herschel found that for induction densities below 2,000 lines per square centimetre, a variation of temperature between 21°C. and 360°C. made no sensible change in the hysteresis loss. Whereas above such induction density it did affect it. Hence, if wrought iron behaves in the same way, the diminution in energy loss in the iron core with rise of temperature in Mr. Marks' experiments must have been wholly due to a decrease of eddy current loss. In a well-designed transformer with sufficient and proper lamination, eddy current loss might be made very small. This would be shown by the diagram of magnetising current and magnetic induction for one complete cycle, practically coinciding with Ewing's determination of the curve of static hysteresis for the same range of induction. If eddy currents are present in large degree then the closed curve $\int i\,d\mathrm{B}$, where i = magnetising

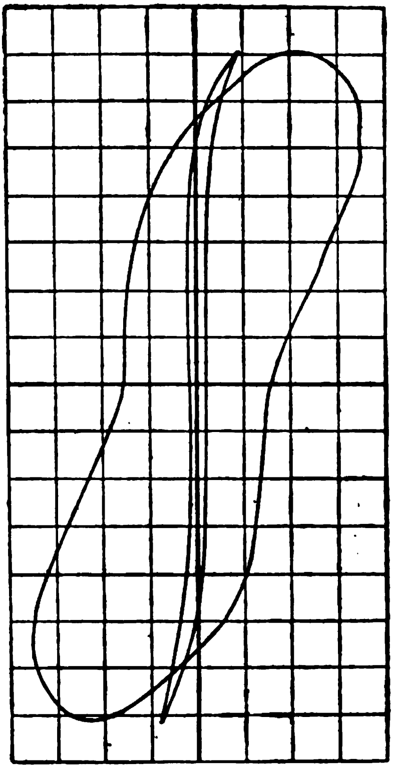

FIG. 32.

current in amperes, and B = total magnetic induction in the core, lies outside of, and includes a greater area than the true hysteresis area. In Fig. 32 is shown a pair of areas, the outer curve is the $\int i\,d\mathrm{B}$ curve for a solid cast-iron ring, 8·6 centimetres in mean diameter, and 2·7 square centimetres in cross-section wound over with 200 turns of wire of negligible resistance (§ 195).

The inner curve in Fig. 32 is the Ewing curve of static hysteresis for the same ring. On the assumption that the true hysteresis loss is constant for all loads then the difference of these areas represents the work lost in eddy currents in the ring.

Core made of wire of B. & S. G. Gauge.	Area of cross-section of coils in sq. cms.	Periodicity.	Induction per sq. cm. in core.	Loss in watts per cubic cm. of core.
1............12	5	169	5,300	·18
2............12	5	177	8,560	·46
3............12	5	177	11,130	·75
4............16	4·9	173	6,000	·14
5............16	4·9	175	9,430	·33
6............16	4·9	167	10,930	·43
7............16	4·9	93	7,250	·10
8............16	4·9	92	13,360	·41
9............16	4·9	45	13,000	·10
10............24	3·56	175	8,150	·19
11............24	3·56	53	8,750	·12
12............36	3·14	173	9,200	·16
13............36	3·14	173	14,900	·29
14............36	3·14	173	18,000 app.	·48
15............36	3·14	96	10,700	·15
16............36	3·14	92	17,800	·33
17............36	3·14	47	18,000 app.	·13
18............36	2·7	160	4,920	·05

It is an important matter to determine in the case of any given core the relative amount of energy dissipated by hysteresis and by eddy currents. Messrs. Fortenbaugh and Sawyer, of Cornell University, have made a determination of the amounts of energy dissipated by cores of iron wire of different gauge, when working at different degrees of magnetisation and different periodicities. The iron wire was simply rusted for insulation. Four iron wire rings were made of a mean diameter of 8·9 centimetres and respectively of gauges No. 12, 16, 24, and 36 (Brown and Sharpe gauge),* and these were wound over with 200 turns of insulated copper wire of negligible resistance. The above table gives the relative loss in these cores when magnetising currents were sent through the coils. The diagram in Fig. 33 shows the losses in these iron cores plotted in terms of the induction for each gauge, periodicity being the same, viz., about 175 ∿. The pure static hysteresis curve of soft iron is given in Fig. 34, in which the loss in ergs per cubic centimetre for slowly-performed cycles is given in terms of the induction. The results for the iron wire rings show, on account of the presence of eddy currents in the case of the larger gauges, a loss varying as the square of the periodicity and as the square of the magnetisation. In the case of the core of No. 36 wire eddy current loss is nearly absent, and the curve differs little from Ewing's curve of static hysteresis for moderately-soft wrought iron. For the cores of Nos. 36, 24, and 16 sizes, there is little difference in the loss below 4,000 lines per square centimetre. At the higher degrees of magnetisation for the finest iron wire, the loss is proportional to the induction density, or to the magnetisation; but for the coarser wire cores the loss varies as the square of the induction. Rise of temperature decreases the electric conductivity of iron by about ·4 per cent. per degree Centigrade at moderate temperatures. Hence, at constant

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* The equivalents of these gauges in decimals of an inch are: 12 = ·08081; 16 = ·05082; 24 = ·0201; 36 = ·005.

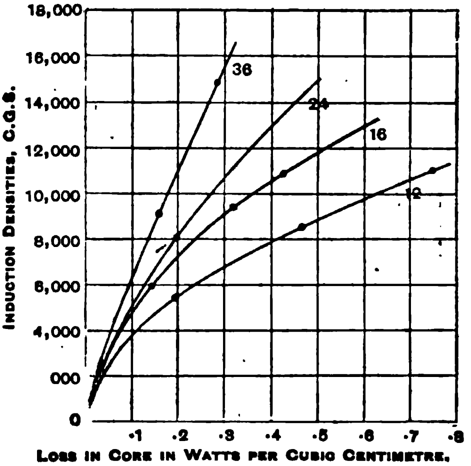

Fig. 33.—∿ =175.

magnetisation, the eddy current strength, and hence eddy current loss, must diminish with rise of temperature. In cores, therefore, in which eddy current loss is predominant, the increase of temperature brought about by the increased copper losses at high loads may, perhaps, be the means of decreasing the total loss in the iron, which some observers have apparently noted. In the experiments of Mr. Marks, with the model transformer, referred to on page 477, we see that if we allow 20 watts for pure hysteresis loss, which is a liberal allowance, the balance of the loss in the core, at about 270°C. and 100°C. respectively, will be 79 – 20 watts and 122 – 20 watts, or about 60 and 100 watts, at temperatures differing by 170°C. This is equivalent to a decrease of loss of 40 watts for 170deg. rise of temperature. Hence the loss is decreased by about a quarter of a watt per degree, and this is roughly about ·4 per cent. of 60. Thus, if Prof. Ewing's experiments above quoted indicate that the pure hysteresis loss in a transformer core is constant for all loads on the secondary, this by no means excludes us from believing that in some types of transformer core the total iron loss may, under the same circumstances, be diminished.

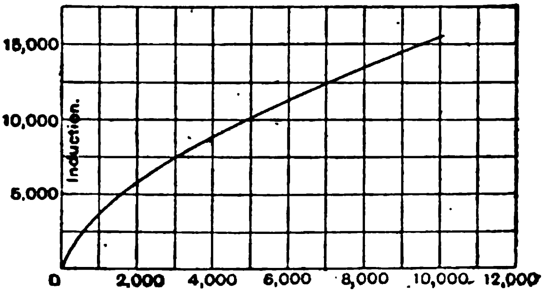

FIG. 34.—Curve of Static Hysteresis for Soft Wrought Iron.

There remains to be considered the question of the relative loss in the same core at different frequencies. Mr. Mordey, in 1889, made some experiments in which he worked the same transformer at different frequencies, and kept it so working until it came to a constant temperature, and he plotted the results on a diagram shown in Fig. 35. From these it is seen that the transformer came after six or seven hours to a constant temperature; and that the temperature, corresponding to a frequency of 100, was less than those corresponding to frequencies of 75 or 125. The higher temperature at the higher frequency is the natural result of the increase of the eddy current loss. The increase of temperature corresponding to the lowered frequency may be due to the fact that at lower frequencies the eddy currents penetrate further into the iron. It must be remembered that just as alternating E.M.F.s create a tendency in electric currents to keep to the surface of their conductors, so alternating magnetomotive forces create a tendency in the magnetic induction to keep to the surface of the iron. In the one case there is a want of penetration in the current below the surface layers, and in the other case a similar behaviour in the magnetism. It cannot be said, however, that there is any absolutely best speed of alternation. In each case the most economical frequency must be decided by many circumstances and by experiment.

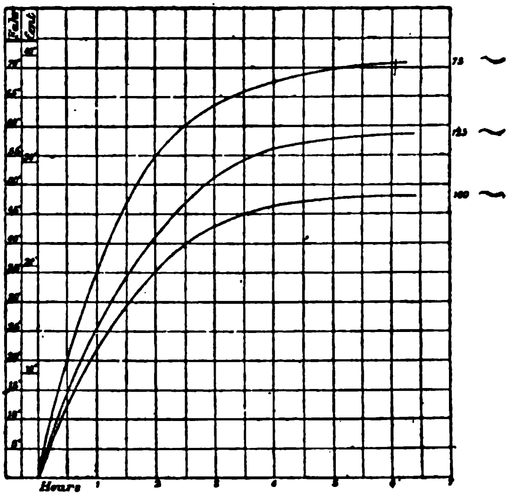

FIG. 35.—Mordey's Curve of Transformer Temperatures at various frequencies.

§ 7. The Pre-Determination of Eddy Currents Loss.—It is necessary at this stage to examine a little more closely into the amount of the eddy current loss in the iron cores of transformers of different kinds. In certain simple cases it is easy to calculate this loss approximately. We shall proceed to calculate the eddy current loss in a core made of round iron wire.

Imagine a core made of a bundle of round iron wire and wrapped over with a magnetising coil, and let a periodic magnetising current flow in this coil so that a simple periodic magnetic induction exists in the iron, the lines of induction being parallel with the direction of the wires. Let b be the mean induction density in the core at any time t, and let B be its maximum value; also let

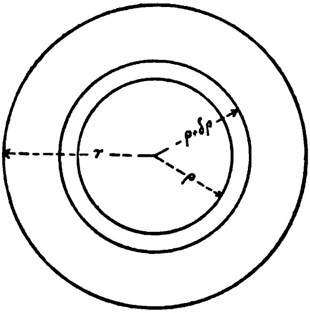

FIG. 36.

$$b = \mathsf{B} \sin p t \quad . \; . \; . \; . \; . \; . \; . \quad (1),$$

where $p = 2\pi$ times the frequency n, as usual. Consider the eddy current loss in one centimetre length of one wire. The lines of flow of the eddy currents in the wire are circles concentric with the perimeter of the wire. Let the circle in Fig. 36 represent the cross section of the round wire of radius r. Take two concentric circles of radius ρ and $\rho + \delta \rho$, and fix attention upon the eddy current flowing in this elementary ring. The total induction through the cylinder at any instant is $\pi \rho^2 b$, and the rate of change of this induction is the measure of the instantaneous electromotive force acting round the elementary cylinder. Call this instantaneous electromotive force e, hence

$$e=\pi \rho^2 \frac{d b}{d t}=\pi \rho^2 \mathsf{B} p \cos p t \quad . \quad . \quad . \quad . \quad . \quad (2).$$

Therefore,

$$e^2=\pi^2 \rho^4 p^2 \mathsf{B}^2 \cos^2 p t \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3).$$

If c is the conductivity at zero Centigrade per cubic centimetre of soft wrought iron,* then if R is the electrical resistance of this elementary cylinder,

$$\mathrm{R}=\frac{2 \pi \rho}{c \delta \rho} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4).$$

Let the instantaneous rate of dissipation of energy in watts in this elementary cylinder be denoted by δw, and then

$$\delta w=\frac{e^2}{\mathrm{R}}=2 \pi^3 c \mathsf{B}^2 n^2 \rho^3 \delta \rho \cos^2 p t\, 10^{-16} \quad . \quad (5).$$

To find the loss over the whole cross section of the wire, we have to integrate (5) between the limits $\rho=o$ and $\rho=r$, and to find the mean or average loss W, we have to take the average value of $\cos^2 p t$ over a period, or to integrate during a complete cycle of values of the induction. The average value of $\cos^2 p t$ for equal small intervals of time during the full period is easily shown to be equal to $\frac{1}{2}$.

Hence we have

$$\mathrm{W}=\frac{\pi^3 c \mathsf{B}^2 n^2 r^4}{4} 10^{-16} \quad . \quad . \quad . \quad . \quad (6).$$

This is the loss in watts for one centimetre length of the wire. Hence the loss in watts per cubic centimetre of the core is obtained by dividing (6) by the volume of one centimetre length of the iron wire, which is πr^2. Call this loss Y. Also let d be the diameter of the wire in centimetres, then $2r = d$. Therefore we have

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* In Dr. J. Hopkinson's Paper on the Magnetisation of Iron (*Phil. Trans.* Roy. Soc. Part II. 1885, page 463) will be found a valuable table of the magnetic and electric properties of various iron alloys, and in particular the specific electric resistance of each kind of iron is given. The specific conductivity of the purest annealed wrought iron per cubic centimetre at 0°C. being 102,000 units, that of grey cast iron is only 9,469 units, that is to say the specific resistance of the softest and purest wrought iron being ·000009638 ohms at 0°C., that of grey cast iron is ·0001056 ohms at 0°C. The coefficient of variation of resistance with temperature of pure iron being ·365 per cent. per degree Centigrade, and that of cast iron only ·083 per cent. per degree.

$$Y = \frac{c\pi^2}{16} d^2 B^2 n^2 10^{-16} \quad . \quad . \quad . \quad . \quad (7).$$

The value of c* is not far from $0{\cdot}102 \times 10^6$, and $\pi^2 c$ is therefore nearly 10^6. It is often more convenient to reckon the diameter of the iron wire in mils (one mil = ·001 inch), because then it can be immediately taken from the tables of wire sizes. But 1 centimetre = 400 mils nearly.
Hence we have, finally,

$$Y = {\cdot}4\, d^2 B^2 n^2 10^{-16} = \frac{(2\,d\,n\,B)^2}{10^{17}} \quad . \quad . \quad (8).$$

This equation (8) gives us the loss in watts per cubic centimetre of a round iron wire core due to eddy currents. Such core being made up of round iron wire of a diameter d mils and subjected to magnetisation of which the maximum induction density is B, and the frequency of alternation n. If the diameter of the wire is measured in millimetres, then for the loss per cubic centimetre we have the expression

$$Y = \frac{d^2 n^2 B^2}{4 \times 10^{12}}.$$

Hence the value of Y is

$$Y = \left(\frac{d\,n\,B}{4 \times 10^5}\right)^2$$ when d is measured in centimetres.

$$Y = \left(\frac{d\,n\,B}{4 \times 10^6}\right)^2$$ when d is measured in millimetres.

$$Y = {\cdot}4 \left(\frac{d\,n\,B}{10^8}\right)^2$$ when d is measured in mils.

Y in all cases being the loss in watts per cubic centimetre of the core.

The above formulæ must not, however, be indiscriminately applied. They are not true, for instance, for solid rods or rings of iron when the frequency is considerable, say 300 ∿, and the diameter of the rod or ring anything much above one or two millimetres. The reason for this is because the eddy currents then mostly circulate in the skin or outer layers of the iron. The magnetic induction does not penetrate into the whole mass, but is more or less confined to the surface. Hence, not all the iron is the seat of eddy currents, and a calculation made by these formulæ would give a number for the eddy current waste in excess of the truth. The formulæ can, however, be applied to cases in which moderate frequencies less than 200 are employed, and to cases in which the iron is as much laminated or as much subdivided as is usually the case in transformer cores.

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* c is the reciprocal of the resistance in ohms at zero Centigrade of one cubic centimetre of iron between two opposite faces.

Since the conductivity of iron, c diminishes with rise of temperature—about ·4 per cent. per degree Centigrade. It is obvious that a rise of temperature from 0° to 100° Centigrade will diminish the eddy current loss by 40 per cent. in any given core.

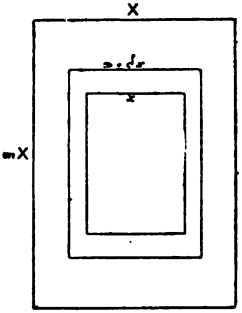

Fig. 37.

Let us compare the results of the formulæ (8) with the table of observed losses in iron wire cores as given on page 481. Take the case of the wire core made of No. 12 wire. The diameter of the wire d, is 80 mils, the maximum induction density B is 5,300, the frequency n is 170. The loss per cubic centimetre by equation (8) is, therefore,

$$\frac{(2 \times 80 \times 170 \times 5{,}300)^2}{10^{17}} = {\cdot}20 \text{ watt per cubic centimetre.}$$

Suppose the ring core came to a temperature of 20° Centigrade. We have then to reduce this ·20 by 10 per cent. The actually observed loss was ·18 watt per cubic centimetre. Hence, the results of calculations by this formula agree very well with those of observation. We can also calculate approximately the eddy current loss in a core made up of iron bands or strips such as those in the core of a Ferranti transformer. Let the lines of induction be parallel with the length of the band. Consider one centimetre in length of a band, of thickness X and depth or width mX. The rectangle in Fig. 37 is the cross-section of the band. We do not know the exact form of the stream lines; but we may, as an approximation, consider that the rectangle is divided into a number of similar concentric rectangles, and that the eddy currents flow round these lines. Consider an adjacent pair of rectangles of sides x and $x+\delta x$, and calculate the eddy current loss in this elementary rectangular tube.

As before, let the induction density at any instant be b, and let

$$b = \mathsf{B} \sin p\, t.$$

Then

$$e = m\, x^2\, \mathsf{B}\, p \cos p\, t \quad . \quad . \quad . \quad . \quad . \quad (9),$$

and

$$e^2 = m^2\, x^4\, \mathsf{B}^2\, p^2 \cos^2 p\, t \quad . \quad . \quad . \quad (10).$$

Also the resistance of the rectangular tube round the rectangle is

$$\mathrm{R} = \frac{2\,x}{c\,m\,\delta\,x} + \frac{2\,m\,x}{c\,\delta\,x} = \frac{2\,x}{c\,\delta\,x}\left(\frac{1+m^2}{m}\right) \quad . \quad . \quad (11)$$

Hence the loss in watts δw at any instant in this element of the one centimetre length of the band is given by

$$\delta w = \frac{e^2}{\mathrm{R}} = \frac{c m^3}{2\,(m^2+1)}\, x^3\, \delta\, x\, \mathsf{B}^2 p^2 \cos^2 p\, t \,.\, 10^{-16} \,.\, (12).$$

Integrating from $x=0$ to $x=\mathrm{X}$, and taking the mean value of $\cos^2 p\, t$ into account we find the total average loss in watts in the one centimetre length of the band is

$$\mathrm{W} = \frac{c\,m^3}{2\,(m^2+1)}\,\frac{x^4}{4}\,\mathsf{B}^2\,\frac{4\,\pi^2\,n^2}{2}\,10^{-16}$$

$$= \frac{c\,m^3\,\pi^2}{4\,(m^2+1)}\,\mathrm{X}^4\,\mathsf{B}^2\,n^2\,10^{-16} \quad . \quad . \quad . \quad . \quad (13);$$

and the loss in watts per cubic centimetre of the band is Y, where

$$\mathrm{Y} = \frac{c\,\pi^2\,m^2}{4\,(m^2+1)}\,x^2\,\mathsf{B}^2\,n^2\,10^{-16}.$$

If the thickness X is measured in mils then we have

$$\mathrm{Y} = \frac{100}{64}\,\frac{m^2}{(m^2+1)}\,\mathrm{X}^2\,\mathsf{B}^2\,n^2\,10^{-16} \quad . \quad . \quad . \quad (14).$$

There is a probability that this equation gives us a rather too great value for the eddy current loss density. It is obvious that the eddy current loss density should be about the same for a round wire as for a square wire of equal cross section. This will be the case if we take the numerical co-efficient in equation (14) as unity instead of $\frac{100}{64}$, and take, as the expression of the loss in watts per unit volume of a rectangular sectioned strip, the value

$$Y = \frac{m^2}{m^2+1} X^2 \mathbf{B}^2 n^2 10^{-16} \quad . \; . \; . \quad (15).$$

If the strip is very wide compared with its thickness then the above becomes $Y = X^2 \mathbf{B}^2 n^2 10^{-16}$ . . . . (16).

X being the thickness of the strip in mils, $\mathbf{B}$ the maximum inductive density, n the frequency, and Y the loss in watts per cubic centimetre of the core made up of the strip. A confirmation of the closely approximate truth of the formula will be given presently.

If $\mathbf{B}$ is measured in *gausses*, or in units such that 10^8 C.-G.-S. units make one *gauss*, then if $\mathbf{B}^1$ is the maximum induction in such units the eddy current loss Y per cubic centimetre of the core is expressed by the following exceedingly simple formula,

$$Y = (X n \mathbf{B}^1)^2 \quad . \; . \; . \; . \; . \; . \quad (17)$$

for a core made up of strip X mils in thickness and for a frequency n.

It may be convenient to append a table calculated from equation (8) for the loss in iron wire cores.

Table *of Eddy Current Loss in Round Iron Wire Cores in microwatts per cubic centimetre, reckoned at 0° Centigrade. For a frequency* ∿ *of 100.*

Induction density B.	Diameter of the wires in nearest B.W.G. number and in mils.				
	10 mils No. 34	20 mils No. 26	30 mils No. 22	36 mils No. 20	50 mils No. 18
1,000	40	160	360	518	1,000
2,000	160	640	1,440	2,072	4,000
3,000	360	1,440	3,240	4,662	9,000
4,000	640	2,560	5,760	8,288	16,000
5,000	1,000	4,000	9,000	12,950	25,000

In applying this table in practice, a correction must be made for temperature, by reducing the above numbers ·4 per cent. for every degree Centigrade above zero, by which the core in its stationary temperature is heated.

§ 8. **Hysteresis Loss in Cores. Steinmetz's Law.**—The hysteretic loss in the iron cores co-exists with that due to eddy currents, and is generally much the larger of the two. It has been found possible to express both of these losses as functions of the induction density. Mr. C. P. Steinmetz has carried out some lengthy investigations on the eddy and hysteretic loss in iron cores.* He has found a very simple empirical law, connecting the hysteretic loss in iron cores with the maximum induction density during the cycle. This is expressed as follows:

Let h stand for the loss in ergs in an iron core per cubic centimetre per cycle of magnetic force. That is, the energy dissipated in making one complete magnetic reversal and back is h ergs per cubic centimetre.

Then, according to Steinmetz,

$$h = \eta\, \mathsf{B}^{1\cdot 6} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (18)$$

where η is a constant, called the hysteretic constant, varying between ·002 and ·005 for ordinary transformer cores, and B is the maximum value of the magnetic induction density during the cycle. Taking Ewing's figures for the hysteretic loss in a soft iron wire, Steinmetz shows that over a range from $\mathsf{B} = 2{,}000$ to $\mathsf{B} = 15{,}600$, the above law holds good, and that Ewing's values can be expressed by the formula $h = \cdot 002\, \mathsf{B}^{1\cdot 6}$ He finds that the law is also true not only for slowly performed cycles, but for cycles at the rate of 100 or 200 per second, and that for such usual commercial frequencies, and for fairly good soft iron cores, the law may be stated that

$$h = \eta\, n\, \mathsf{B}^{1\cdot 6} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (19).$$

If H is the loss in watts per cubic centimetre of the core, then

$$\mathsf{H} = \eta\, n\, \mathsf{B}^{1\cdot 6}\, 10^{-7} \quad . \quad . \quad . \quad . \quad . \quad (20).$$

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* See *Electrician*, February 12th, 19th, and 26th, 1892, p. 385, Vol. XXVIII. See also *Journal of the American Institute of Electrical Engineers*, January 19, 1892.

Mr. Steinmetz has ascertained the values of this hysteretic constant η for different kinds of iron and cores, and they are as follow :—

Hysteretic Constants for Different Materials.

Material.	Hysteretic constant η.	Material.	Hysteretic constant η.
Very soft iron wire......	·002	Soft annealed cast steel	·008
Very thin soft sheet iron	·0024	Soft machine steel......	·0094
Thin good sheet iron ...	·003	Cast steel................	·0120
Thick sheet iron	·0033	Cast iron..................	·0162
Most ordinary sheet iron transformer cores.....	·004 or ·0045	Hardened cast steel....	·025

There is some evidence to show that the values of η are increased by increasing the frequency of the reversals.

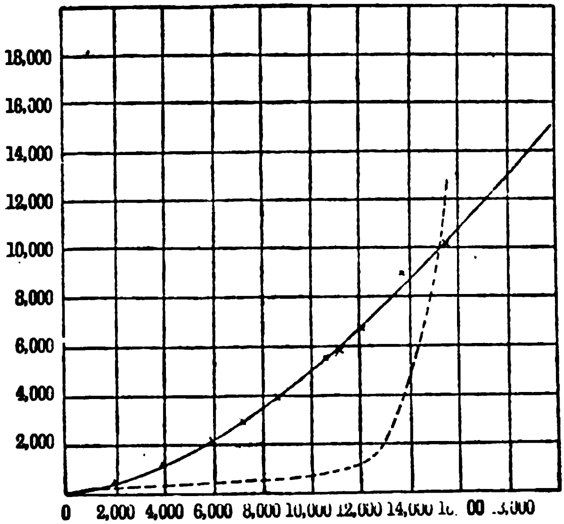

Fig. 38.

The close coincidence of the results of calculation by this empirical law with the results of observation are shown in the curve in Fig. 38, in which the results of Ewing's determinations of hysteretic loss for slowly performed cycles are marked with crosses, and the curve is drawn in from the equation $h = \eta\, B^{1\cdot6}$.

The horizontal abscissæ are induction densities, and the vertical ordinates hysteretic loss in ergs per cubic centimetre per cycle. The constant coefficient η, which Steinmetz calls the *hysteretic coefficient*, is according to him a function of the frequency of the alternations, as well as dependant upon the quality of the iron. For a core built up of very thin soft iron plates, he found that the value of η could be expressed by

$$\eta = (\cdot 0017 + \cdot 000016\, n - \cdot 00000003\, n^2).$$

It therefore increases with the frequency. For a frequency of 100, $\eta = \cdot 0033$, nearly, for good thin sheet iron or fine wire cores. We can therefore express the whole loss, W, in watts per cubic centimetre in a transformer core by a function of $n\,\mathsf{B}$ and certain constants; thus,

$$W = \alpha\, n\, \mathsf{B}^{1\cdot 6} + \beta\, n^2\, \mathsf{B}^2 \quad . \quad . \quad . \quad . \quad (21),$$

where the first term is the hysteresis loss and the second the eddy current loss, and α and β are certain constants which depend upon the kind of iron used, its degree of lamination, its temperature, and to a small degree upon the frequency. The value of the first term is not much affected by the temperature of the iron; the magnitude of the second, however, is greatly reduced by rise of temperature.

As an example of the close agreement between observation and the above theory we may instance one measurement out of a large number made by Mr. Steinmetz on the loss in iron cores. A small transformer had a core built up of iron plates 2·54 cm. in width and ·068 cm. in thickness. This plate thickness expressed in mils is 27·2 mils.

According to equation (16) the loss due to eddy currents in this core in watts per cubic centimetre should be

$$(27\cdot 2)^2 n^2\, \mathsf{B}^2 = 740\, n^2\, \mathsf{B}^2.$$

Mr. Steinmetz found that the observed total loss in watts per cubic centimetre in this core could be expressed by the empirical formula

$$W = \cdot 0033\, n\, \mathsf{B}^{1\cdot 6} + 746\, n^2\, \mathsf{B}^2 \quad . \quad . \quad . \quad (22).$$

Accordingly it appears that we can predetermine with some degree of accuracy the losses in a transformer core when we know the frequency, the thickness of the plates, and the value of B. B can be found directly from the secondary electromotive force, for if E_2 be the $\sqrt{\text{mean}^2}$ value of the secondary electromotive force then

$$\frac{cl}{A} \approx \mathsf{B} = \frac{E_2\sqrt{2}\,10^8}{2\pi n S N_2}.$$

S being the cross-sectional area of the core.

According to Steinmetz the hysteretic constant η varies considerably for different kinds of iron, but for every kind the hysteresis per cycle per unit of volume varies as the 1·6th power of the maximum induction during the period. So far as chemical constitution is concerned, the purer the iron the lower the hysteresis, whilst any foreign matter in or hardening of the iron increases it. Especially does the presence of manganese increase it immensely, whilst chromium and tungsten much less, and carbon and silicon least of all. An increase of hysteresis is always accompanied by a decrease of magnetic susceptibility.

In order to aid in comparing the results of observation with this empirical formula, we append a Table of the values of B from 1,000 to 10,000 and the corresponding values of $\mathsf{B}^{1\cdot6}$, and of the products of $\mathsf{B}^{1\cdot6}$ and ·002, ·003, ·004, ·005.

Table *of Hysteresis Losses in Good Soft Iron, calculated from the formula* $W = \eta\, n\, \mathsf{B}^{1\cdot6}\, 10^{-1}$, *in microwatts per cubic centimetre, for a frequency* $\sim$ *of* $n = 100$ *for various maximum inductions.*

Maximum induction density B.	Value of $\mathsf{B}^{1\cdot6}$	Values of $\eta\, n\, \mathsf{B}^{1\cdot6}\, 10^{-1}$.			
		$\eta = \cdot002$.	$\eta = \cdot003$.	$\eta = \cdot004$.	$\eta = \cdot005$.
1,000	63,100	1,262	1,893	2,524	3,155
2,000	191,300	3,826	5,739	7,652	9,565
3,000	365,900	7,318	10,967	14,636	18,295
4,000	580,000	11,600	17,400	23,200	29,000
5,000	828,800	16,576	24,864	33,152	41,440
6,000	1,111,000	22,220	33,330	44,440	55,550
7,000	1,420,000	28,400	42,600	56,800	71,000
8,000	1,758,000	35,160	52,740	70,320	87,900
9,000	2,122,000	42,440	63,660	44,880	106,100
10,000	2,511,000	50,220	75,330	100,440	125,550

From this Table and the one before, giving the eddy current losses in iron cores, we see that for a given maximum induction density the eddy current loss per unit of volume will be roughly equal to the hysteresis loss if the core is made up of iron wires, each ·02 of an inch in diameter. As the wires of a wire core are always selected of a smaller diameter than this, we see that in general the eddy current loss will be much less than the hysteresis loss. This points also to the fact that if there could be found any way of debasing the electrical conductivity of the iron without deteriorating its magnetic permeability and without increasing its hysteresis, this change would be a valuable improvement. Unfortunately, iron of good magnetic permeability always appears to be iron of large electrical conductivity.

Some very interesting experiments were made by Mr. Alexander Siemens on the iron core losses of Siemens Bros.' Cable transformers.*

In these experiments the rate at which energy was being dissipated in the iron core when the transformer was at work was estimated by the rate of rise of temperature of one of the iron wires forming the core. The rise of temperature of this wire was estimated by its change in electrical resistance. This test wire was insulated by cotton covering from the rest of the wires forming the core.

This mode of constructing transformers was foreshadowed by Dr. Werner von Siemens, who proposed in his patent, No. 42 of 1886, to surround the primary and secondary circuits of a transformer with iron wire, but his experiments gave no satisfactory results.

The subject was recently taken up again, and the present form of these transformers was suggested by Mr. Dieselhorst and Dr. Baur.

The principal advantage which is claimed for this form of transformer is that it can be made by machinery, in the same way as a submarine cable is made, the employment of manual labour in putting it together being entirely avoided.

A special machine has been designed and erected for completing such transformers in one operation, after the iron core has been prepared on an ordinary rope-stranding machine.

Besides offering these facilities for manufacture, the peculiar shape of the cable transformer lends itself to a variety of useful applications.

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* *See* a Paper by Mr. Alexander Siemens in the *Proc.* Institution of Electrical Engineers, February, 1892; also see *Electrician*, Vol. XXVIII., p. 431, 1892, "Some Experimental Investigations in Alternating Currents."

The transformer used for the experiments had a core of 900 soft iron wires, each 1mm. in diameter by 6 metres long, twisted up in the form of a rope, and surrounded by two windings of copper wire, properly insulated, the one for high voltage and the other for low voltage.

From the fact that the diameter of the transformer is very small compared to its length, it follows that the magnetic field, and consequently the induction in the iron core, is uniformly distributed, with the exception of a slight drop at either end.

The mean induction produced by passing an alternate current through the low-voltage circuit was measured by the difference of potential obtained in the high-voltage circuit while no current was passing through the latter.

The temperature of the iron core was ascertained by measuring the increase in the electrical resistance of one of its wires, which had been insulated from the rest by a cotton covering.

By actual comparison it was found that one of the wires near the periphery gave, within the limits of errors of observation, the same results as the central wire, so that the exact position of this "test wire" has no influence on the result; the heating of the cotton insulation can be neglected, as its mass is so very small compared with that of the iron.

Separate tests were made to determine the specific heat of the iron, which was found to be = 0·112, and the temperature coefficient for the electrical resistance of the test wire, which was equal to 0·0054.

The current was kept on for a short time only, as it was desired in the first instance to determine the rate at which energy is converted into heat in such a transformer, and the rise in temperature after keeping the current on for *s* seconds can be calculated from the formula,

$$t_s = \frac{R_s - R_0}{\cdot 0054 . R_0},$$

where R_0 = electrical resistance before starting the current, and R_s = electrical resistance after keeping the current on for *s* seconds.

During the time that the current passes, the test-wire will lose a certain amount of heat by radiation and convection, although it is surrounded by all the other iron wires, which are heated in a similar manner. This loss can, however, easily be allowed for by plotting a "cooling curve" after the passage of the current has been stopped, with times as abscissæ and temperatures as ordinates. In this way the rise of temperature of the iron core per second was observed with an alternate current of 100 ∿ per second, varying in strength so as to produce a different induction for each observation.

Considering that the loss of energy caused by the heating of the iron as proportionate to its mass, to its specific heat, and to its rise of temperature per second, it was possible to plot a curve

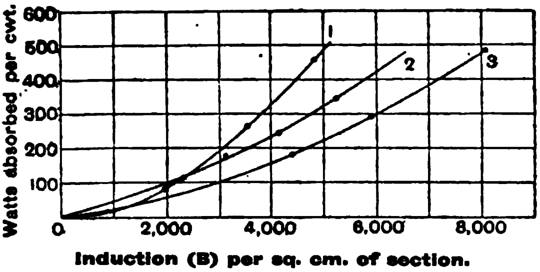

FIG. 39.

Total loss of energy per cwt. in wire cores of soft iron wire 1mm. in diameter at various inductions.—Curve 1, frequency = 133 ∿ per second. Curve 2, frequency = 100 ∿ per second. Curve 3, frequency = 66·7 ∿ per second.

in which the maximum number of C.-G.-S. lines per square cm. are the abscissæ, and the losses of energy are represented as ordinates calculated for the mass of 1 cwt. of soft iron wires 1 mm. in diameter.

The results of these observations on the total waste of energy in the core are plotted in curves in Fig. 39, in which the horizontal abscissæ are maximum induction densities, and the vertical ones the waste of energy in 1 cwt. of the core in watts. The three curves correspond to three different frequencies. Taking these total wastes we can reckon out from the Table on p. 490 the total loss due to eddy currents alone, and, deducting this from the total loss, obtain the values of the hysteresis waste. This has been done in the Table below.

Experiments *on the Iron Core Losses in a Siemens Cable Transformer at a Frequency* (∿) *of 100 for various Inductions. The core consisted of iron wires, 1mm. in diameter.**

Mean maximum induction density B in the core.	Total observed loss in watts per cwt. in the core T	Calculated eddy current loss in watts per cwt. E	Hysteresis loss estimated by difference in watts per cwt. H.
1,000	43·2	4	39·2
2,000	96·2	16	80·2
3,000	158·0	36	122·0
4,000	231·2	64	167·2
5,000	309·5	100	209·5
6,000	390·1	144	246·1

By deducting in this way the calculated eddy current loss from the total observed loss in the core, a Table was constructed of pure hysteresis losses for various frequencies, and for various inductions. The results of these calculations are shown in Fig. 40, in which the hysteresis losses for various inductions are plotted for frequencies of 66·7 and 100, and also a curve of static hysteresis is appended. It will be seen, therefore, that Mr. Siemens' experiments agree with those of Mr. Steinmetz in indicating an increase in hysteresis waste, with increase

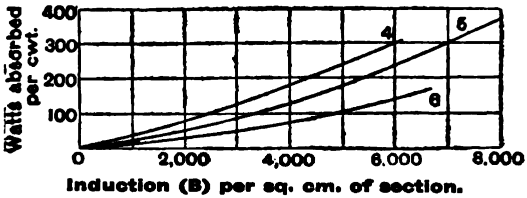

FIG. 40.

Loss by hysteresis in iron wire cores.—Curve 4, frequency = 100 ∿ per second. Curve 5, frequency = 66·7 ∿ per second. Curve 6, static hysteresis according to Prof. Ewing.

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* The Table has been recalculated by the author, because in the original Paper by Mr. Siemens, a slip occurs in the calculation of the eddy current loss which makes the resulting values too small by about 20 per cent.

in frequency. In other words, that there is a kinetic and a static hysteresis, or, as it had better be called, a slow-cycle, and a rapid-cycle value for the hysteresis waste. The evidence for this rests, however, on the accuracy of calorimetric observations, which are difficult to make. On the whole it may be well yet to suspend judgment as to whether there is a real increase in the true hysteresis losses in iron cores with increase in the speed at which the cycle is performed. On examining the table of hysteresis losses for the cable transformer it will be seen that the hysteresis loss is proportional to the induction density simply, and not to the 1·6th power. The total loss W in watts per cubic centimetre of the core of the Siemens' cable transformer is very nearly expressed by the equation

$$W = \left(\frac{d n \mathrm{B}}{4 \times 10^6}\right)^2 + \frac{\cdot 625\, n \mathrm{B}}{10^7} \quad . \quad . \quad . \quad (22).$$

The first term on the right-hand side represents the eddy current loss, and the second term the hysteretic loss. In this equation d is the diameter of the iron wires in millimetres and n is the frequency. On the other hand, it is found by trial that the total loss W, in watts per cubic centimetre, of the iron core of the wire core transformers employed by Messrs. Fortenbaugh and Sawyer in the experiments described on page 481, can be very nearly expressed by Steinmetz law, viz.,

$$W = \frac{4 d^2 n^2 \mathrm{B}^2}{10^{17}} + \frac{\cdot 004\, n \mathrm{B}^{1\cdot 6}}{10^7} \quad . \quad . \quad . \quad (23),$$

where d is the diameter of the wire in mils and n is the frequency. For the last equation it is easily seen that for the induction density most generally used in cores, viz., a maximum of 4,000, and for wire cores composed of wires 1 mm. in diameter, and for a frequency of 100, the total loss in watts in the core is about 1 watt for every 30 cubic centimetres of core volume, such loss being about two-thirds hysteretic loss and one-third eddy current loss. Hence for this or for any other induction density, if the total core waste to be allowed is known, the volume of the core which will permit this to be the case can be predetermined. As an illustration of the application of the foregoing principles to a real case, let us predetermine the total losses in the iron core of the small Westinghouse Transformer used by Prof. Ryan in the experiments described on page 445. The transformer core consisted of iron plates one-half millimetre, or 20 mils, thick. The total volume of the core was 2,050 cubic centimetres, the maximum induction density 3,850, and the frequency 138. Required to find the total losses in this core. We have then $X=20$, $n=138$, $B=3{,}850$. Hence the eddy current loss per cubic centimetre is, by equation (16), equal to

$$(20)^2 \times (138)^2 \times (3{,}850)^2 \times 10^{-16} = \cdot 011 \text{ watt},$$

and the hysteresis loss per cubic centimetre is, by equation (20), equal to

$$\cdot 0045 \times 138 \times (3{,}850)^{1\cdot 6} \times 10^{-7} = \cdot 036 \text{ watt}.$$

Hence the complete loss is ·047 watt per cubic centimetre, and the total loss in the whole core nearly 96 watts. The actually observed loss was 95 watts.

§ 9. The Practical Construction of the Transformer.—Before proceeding to consider the question of the design of transformers, it will be desirable to make some reference to practical processes of construction. Two distinct matters present themselves to the constructor: the first of these is the cost of construction; the second the performance of the apparatus when made. The intelligent manufacturer aims at producing the best appliances at the possible lowest cost. In doing this he has to consider all kinds of questions, such as the ease of manufacture and repair, and to achieve the best results in this direction without sacrifice of efficiency in the end. A form of transformer which may be, theoretically, very perfect, may have very small practical use if the superior difficulties of manufacture of the most perfect form rule it out of the market in competition with other less perfect, but more practical forms.

A ring of fine iron wire wound closely over with two intertwined circuits would present several theoretical advantages as a transformer; but such an ideal form is difficult to wind and expensive to repair, and accordingly is not a good form of commercial transformer to employ.

Beginning, then, with the conducting circuits, from what has been already said the reader knows that the constructor has to make, in the first place, the iron core, either a closed or an open magnetic circuit, and to wind this over with two distinct and insulated circuits of wire. In some old forms of transformer, such as the old Zipernowsky form, these circuits were wound on the iron core directly by hand. At present the almost universal practice is to wind these primary and secondary circuits first on a *former* or frame. If the coil is to remain on this frame or bobbin, then this last is generally formed of ebonite or porcelain, or some good insulator. The circuits generally consist of copper wire or strip, double covered with cotton, or insulated with vulcanized fibre or japanned paper.

Speaking generally, it is not a good plan to trust too much to shellac varnish or layers of shellaced calico as an insulator. When cotton fibre is dried and shellac-varnished, it is a good insulator for a time, but it soon becomes capable of absorbing moisture; and, moreover, if the transformer gets hot it seems as if the shellac carbonises very readily at a low temperature, and then rapidly becomes conducting.

Each primary and secondary circuit should be split up into a number of coils, so arranged that no two adjacent layers of wire are at any great difference of potential. Next comes the question of insulating the primary coil from the secondary coil, and both coils from the iron bands. This needs very great attention. Mica is very often used for this purpose, also ebonite and porcelain. Layers of shellaced cloth or paper are most commonly employed, but do not make a satisfactory permanent insulation, neither does baked and shellaced vulcanized fibre. Later on we shall show how the section and length of wire in both coils is to be calculated for a given transformer; but at present, assuming this known, we have to do merely with practical details. The coils being wound and insulated, whether on frames or not, have next to be built up round the core, or the core made to enclose them. In any case, what has to be done is to provide an iron path for the lines of force. This may take endless different forms, several of which have been illustrated in the previous chapters.

Roughly distinguishing, we may say the core takes one of four forms—1st. Stampings of sheet iron of an E shape are put together over the coils, face to face, so as to form a double path for the lines of force. Of this type are the Mordey Transformer, the latest-pattern Ganz Transformer, and the Westinghouse

Transformer. The new Ganz Transformer consists of a pile of E-shaped stampings of sheet iron, which are compressed and fixed with the back of the E to a round iron disc. A pair of these discs are then placed face to face, and held together by tie-rods. The primary and secondary coils, wound on frames, are slipped on to the middle bar of the E, the faces of the iron stampings being planed, so that where opposed edges of the stampings meet they make a good magnetic joint. The tie-rods hold the halves of the core together, yet they can be separated in a few minutes to get at or replace a coil. The second type is that represented either by a Ferranti Transformer, or by such a form as that shown in Fig. 41, which has been used by Messrs. Kapp, Snell, and Wright, and revived recently by Messrs. Pyke and Harris. In this form the two coils, primary and secondary, are overlaid and then clad in iron, either as is done by Ferranti or as shown in Fig. 41, by slipping split U-shaped or split frame-shaped sheet iron stampings over both coils to enclose them round with iron. A third typical form is that represented either by a Swinburne Hedgehog Transformer, or by a Siemens Cable Transformer. In this case the magnetic circuit is an open circuit, that is one not completely consisting of iron. The Siemens Cable Transformer is made by winding the two circuits, primary and secondary, on to an iron rope, which forms the core. A certain

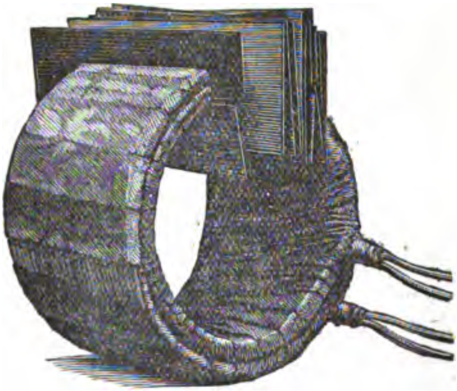
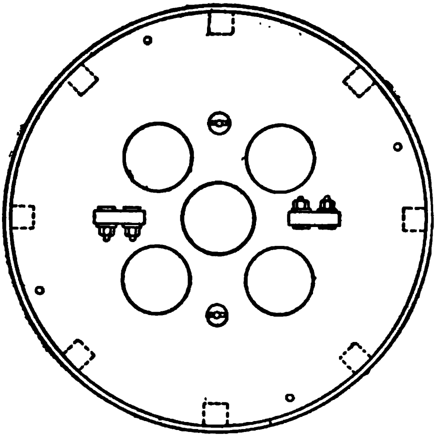


FIG. 41.—Wright's "Brighton" Transformer in Process of Manufacture, showing Method of Slipping Plates over Coils.

length of this cable depending on the size and transforming power of the core is then wound spiral fashion on to a frame (*see* Fig. 42), and forms an open circuit transformer of a very effective character. In this particular form of transformer the primary and secondary circuits are so completely interwound that magnetic leakage is almost absent. The illustrations



Siemens' "Cable" Transformer. Plan.

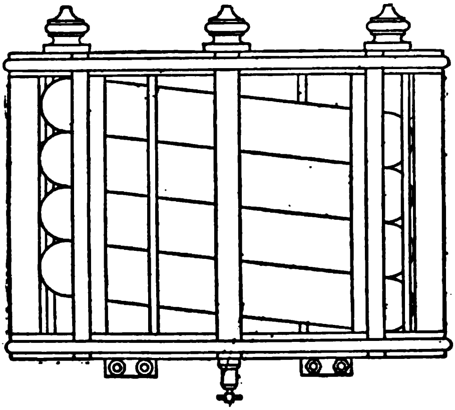


Fig. 42.—Siemens' "Cable" Transformer. Elevation.

show in plan and elevation a cable transformer coiled and fixed for use in a skeleton stand, with the terminals of the primary and secondary circuits arranged on the top. There is a large cooling surface in proportion to the output, and a high efficiency and small "drop." Thus the 150 horse-power transformer would weigh about 30 cwt. in all with stand. It would have an efficiency of 94 per cent. at full load, 93 or 94 per cent. at half load, and 90 per cent. at quarter load, and the "drop" at the secondary terminals between full and no load would be between 3 and 4 per cent. The weights of the 10, 50, 100 and 200 horse-power sizes with stand are respectively 5·5, 13·5, 22·5, and 42 cwt. In the fourth form we have a laminated closed iron circuit, which is wound over Gramme ring fashion, with primary and secondary coils. The coils are either overlaid, as in the Lowrie-Hall Transformer (*see* Fig. 75, p. 226) or sandwiched in between one another, as in the form shown in Fig. 49 (p. 90), due to Dr. Hopkinson. Many other forms are possible. In the Schuckert Transformer, for use with, what are called, polyphase or rotary field alternators,

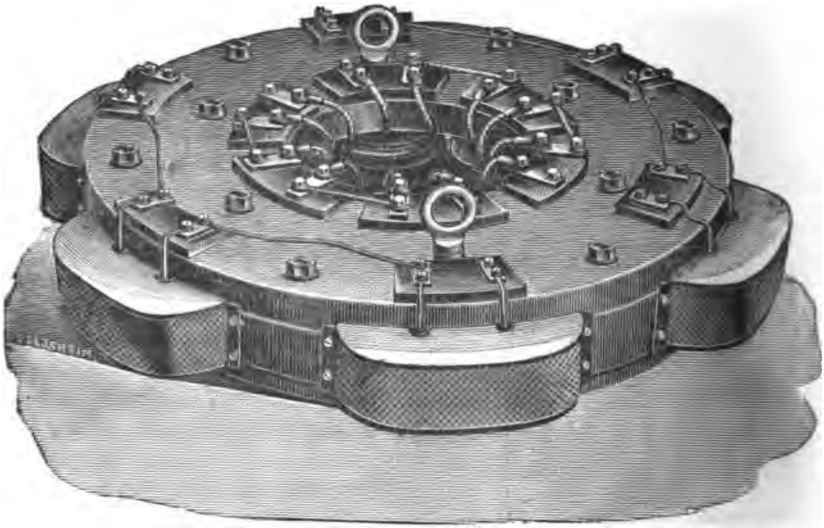


FIG. 43.—Schuckert Polyphase Transformer.

the iron circuit consists of iron strip rolled up into a flat disc by being wound in a spiral form, grooves are then planed out in this disc (see Fig. 43), and coils fitted into these grooves. A lid, similarly formed, is then fastened on by bolts so as to complete the magnetic circuit (see Fig. 44).

In the transformers used with the "Drehstrom" or rotary field dynamos, the iron circuit is somewhat differently disposed. Space will not permit us to enter into a description of the dynamos and mode of operation of the polyphase, Drehstrom, or rotary field system, as it is variously called. Suffice it to say, that in this system there are three or more circuits, each of which is traversed by an alternating current, the various alternating currents in these circuits differing in phase by equal amounts. Hence, the corresponding transformer has to be made with three or more primary coils, and the same number

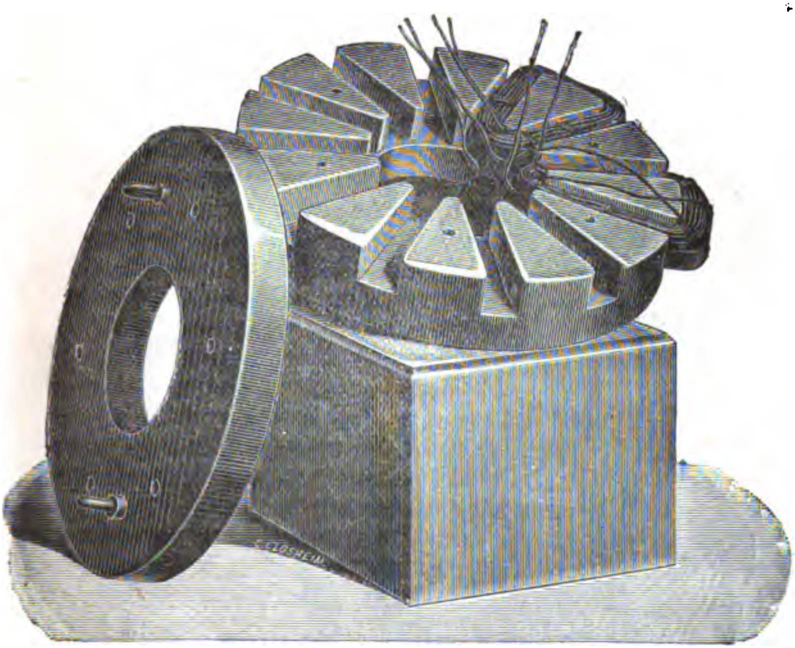


FIG. 44.—Core of Schuckert Polyphase Transformer.

of secondary coils. It will be sufficient to describe one form viz., that of Dobrowolsky.

This transformer, in the form used in the Frankfort-Lauffen high-tension transmission (1891) experiments, consists of three linear iron wire cores.

These are connected at the top and bottom by a laminated iron ring (*see* Fig. 45), and each core is wound with a primary and secondary circuit. The primary coil is separated from the secondary coil by a porcelain insulating sheath. The completed transformer (*see* Fig. 46) is put into an iron case and sealed up in oil. The mode of connection of the armature circuits and transformer circuits is shown in Fig. 47, which represents the arrangement as used in the experiments at Frankfort in 1891, in which power was transmitted for a distance of 109 miles at a pressure of 10,000 to 25,000 volts.

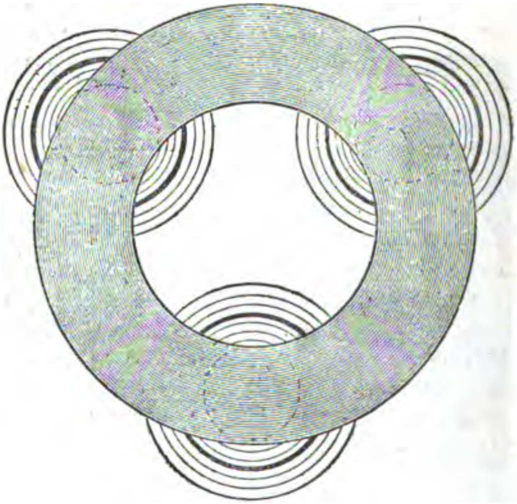


Fig. 45.

The three circuits of the armature of the "Drehstrom," or three-phase alternator, are represented in Fig. 47. Each of these circuits is in turn the seat of an alternating E.M.F. force, which sends an alternating current out along the line and back by the return wire, which was kept at zero potential by being "earthed" In the Frankfort-Lauffen experiments the current was generated

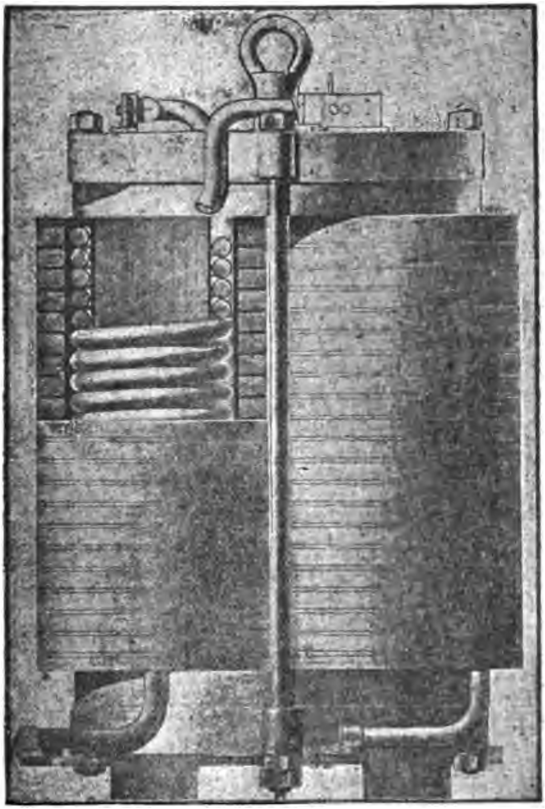


FIG. 46.—Elevation of Three-phase Transformer as used in the Frankfort-Lauffen Experiments of 1891.

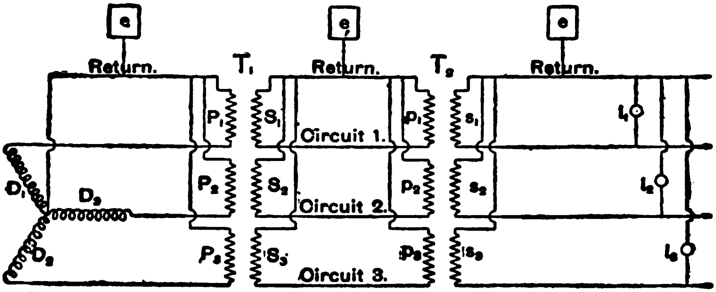


FIG. 47.—Three-phase or Drehstrom System of Transformer Transmission.

D_1 D_2 D_3—Three armature circuits of dynamo. P_1 P_2 P_3—Three primary circuits of step-up transformer T_1. S_1 S_2 S_3—Three secondary circuits of step-up transformer T_1. P_1 P_2 P_3—Three primary circuits of step-down transformer. S_1 S_2 S_3—Three secondary circuits of step-down transformer. L_1 L_2 L_3—Lamps or motors.

at a pressure of 50 volts, and then raised in pressure by the transformers for transmission.

At the receiving end it was reduced in pressure again to the same amount. The transformers used had a power of 200,000 watts and a transformation ratio of 1 : 160, and they therefore could raise the pressure of 78 volts existing between any two wires of the dynamos to 12,500; and by using two transformers in series to 25,000 volts. The number of complete alternations was 40 per second.

§ 10. **The Practical Testing of Transformers.**—In testing the insulation of a transformer between the primary and secondary coils any process of measuring the insulation resistance with a galvanometer and a Wheatstone's bridge, or similar methods using low continuous potentials, is a perfectly useless performance. Those not experienced in these things often consider that some sort of safeguard for the performance of a transformer is found in specifying for a certain number of thousand ohms or megohms of insulation. This, however, is erroneous. The only really useful tests consist in exposing the different portions of the insulation of the transformer to electric pressures of two or three times that which in practice will come upon them, and subjecting them to this increased pressure for a sufficient time. Every transformer should be subjected to the following tests before being accepted, and put into use:—A pressure in alternating volts, equal at least to double the high-tension pressure at which it is to be worked, should be applied between the primary coil and the secondary coil, and between the primary coil and the iron bands or plates or iron case. This pressure should be kept on for at least an hour. If the transformer stands this test, it is probably in good order. In the next place, the magnetising current of the transformer when on open secondary circuit should be measured. This should be done both on the low-pressure or the high-pressure sides. A large magnetising current is, for several reasons, undesirable. Owing to their less relative primary circuit self-induction, open iron circuit or open magnetic circuit transformers, size for size, require larger magnetising currents than closed iron-circuit transformers. That is to say, if we take, for instance, a 5 H.P. Swinburne

Hedgehog Transformer, we shall find that when on open secondary it takes more primary current than a Mordey or a Westinghouse Transformer of the same size. This in itself is a disadvantage in some ways. Mr. Swinburne has proposed to meet this difficulty by placing a condenser across the primary terminals of the transformers. We have seen in § 9 (p. 391) of Chapter III. that if a condenser is short-circuited by an inductive resistance, the current in this shunt may, under proper conditions as to capacity and self-induction, be greater than the main current before division. Hence, we can as it were produce the necessary magnetising current for the transformer out of a condenser, and avoid actually generating it. The production of a good economical condenser capable of working at pressures of 2,000 or 2,400 volts is, therefore, an important matter, and would enable the magnetising current for such open-circuit transformers to be supplied without increase of current producing capacity in the generating plant. In addition to the foregoing tests an examination should be made of the "drop" in the secondary circuit between full load and no load. If this is more than 5 per cent. of the secondary pressure at no load, the transformer will have a very limited use. In testing large transformers it is, of course, desirable to analyse this "drop," and find out how much of it depends on true magnetic leakage, and how much on true copper resistance. This is easily done when the currents and true ohmic resistances of the circuits are known.

A most important matter is the question of heating. Special tests should be made before extensively employing any particular pattern of transformer, to ascertain the stationary temperature at which that transformer arrives when worked continuously at either full load or no load; the latter being the most important. The transformer should have thermometers inserted into it in various places, and an hourly record of temperature taken, and note made of the time at which the temperature becomes approximately stationary. This ought not to exceed 150° Fahr. A high temperature at no load is the result of a badly designed iron core or too large a magnetising current. In either case the result is a waste of energy and danger of carbonising the insulation. In the case of large transformers good ventilation of the core is essential. In the case of oil-insulated transformers, convection comes into play to assist in the removal of the heat; and special devices have been suggested for causing a circulation of oil round and through the transformer. Messrs. Pyke and Harris and others have employed such oil-circulating devices, both in connection with induction coils and transformers. In this case the heated oil is made to rise upwards and pass by convection through a cooler and then flow down again. In the case of large substation transformers a system of water-cooling pipes might also be similarly employed.

§ 11. The Predetermination of the Primary Current of Transformers on open Secondary Circuit.—When an alternating electromotive force is applied to the primary terminals of a transformer with open secondary circuit, or to the terminals of a simple choking coil, a small current is found to flow through the circuit, which is commonly, but rather erroneously, called the "magnetising current." It would be better to call this the "core" current, because its magnitude is very largely dependent upon actions taking place in the iron core. If a given conducting circuit, say an insulated copper wire, is wound on a bobbin non-inductively, and a certain alternating electromotive force applied to the ends of the circuit, it is a very easy matter to calculate the ampere value of the current, which will under these circumstances flow through the circuit. For the $\sqrt{\text{mean}^2}$ value of the current is at once obtained by dividing the $\sqrt{\text{mean}^2}$ value of the electromotive force by the ohmic resistance (R) of the wire. Again, suppose that this same circuit is wound inductively on a non-magnetic and non-conducting core or bobbin, the circuit has then a definite inductance (L), and the $\sqrt{\text{mean}^2}$ value of the current is obtained by dividing the $\sqrt{\text{mean}^2}$ value of the electromotive force by the impedance ($\sqrt{R^2 + p^2 L^2}$) of the circuit. In both these cases the energy supplied to the circuit is simply dissipated in the form of heat in the copper circuit. If, however, we suppose the copper circuit to be wound inductively on a magnetisable core, the problem of predetermining the current is not quite so simple. If the core is an ordinary iron core, then the energy supplied to the circuit is taken up in three ways—(i.) it is partly dissipated as heat in the copper circuit; (ii.) it is further dissipated by true magnetic hysteresis waste in the iron core;

and (iii.) it is also wasted by reason of eddy currents set up in the core. A little reflection will show that the final result of both hysteresis and eddy current waste is equivalent, as far as energy waste is concerned, to closing a secondary circuit round an ideal non-hysteretic and non-conducting core. For we may imagine that the energy waste due to all the little eddy currents in the core and that due to the magnetic reversals to be imitated by simple resistance waste of a secondary current of a certain magnitude flowing in a closed secondary circuit wrapped round a perfectly ideal iron core in which these wastes do not go on. We have seen that the effect of the secondary circuit, when closed, is to advance the phase of the primary current, and to increase its mean value. Hence, we may conclude that the total effect of the eddy currents and the hysteresis losses in an iron core upon the phase and magnitude of the so-called magnetising current is to increase its magnitude, and to bring it more into consonance with the impressed electromotive force as far as phase is concerned.

This action introduces further difficulties into the problem of predetermining the magnetising current of a transformer, or the current flowing through a choking coil when subjected to a certain alternating electromotive force of determined magnitude and frequency.

The general solution of this problem is a rather difficult matter; but we shall see that fortunately it may be easily solved for the cases most likely to occur in practice.

For the moment let us suppose ourselves dealing with a core in which both eddy current and hysteresis waste are so small as to be negligible, and consider, under these circumstances, how the magnitude of the current flowing through the primary circuit when the secondary circuit is open is to be determined.

Let R be the true resistance of the primary circuit, e the instantaneous value at any time of the impressed electromotive force acting on this circuit, and let i be the value of the current flowing through the circuit at that same instant. Also, let S be the cross-section of the magnetic circuit or of the core, and l be its mean length, and N the number of turns of the primary current round the core, and n the frequency of the alternations. Let b be the value of the induction density in the core at the instant of time considered.

We shall suppose the electromotive force to be a simple periodic function of the time, as usual, so that,

$$e = \mathrm{E} \sin p\, t.$$

If, then, μ is the value of the true magnetic permeability of the core at the instant when the induction density is b, the relation between i and b will be expressed by the equation,

$$4\pi \frac{\mathrm{N}}{l} \mu i = b \quad \ldots\ldots\ldots \quad (1).$$

If instead of measuring i and b in C.-G.-S. or absolute units we measure i in amperes and b in gausses* per square centimetre then equation (1) becomes,

$$\frac{4\pi}{10^9} \frac{\mathrm{N}}{l} \mu i = b \quad \ldots\ldots\ldots \quad (2).$$

These equations immediately follow from the facts that the magnetic force in the interior of a closed solenoid is by a fundamental principle equal in magnitude to 4π-times the absolute current turns per unit of length of the solenoid, and also that the quotient of induction density by permeability is a measure of the magnetic force in the interior of the core. From (2) it immediately follows that,

$$\frac{4\pi}{10^9} \frac{\mathrm{S\,N}^2}{l} \mu i = \mathrm{S\,N}\, b \quad \ldots\ldots \quad (3);$$

and that

$$\frac{4\pi}{10^9} \frac{\mathrm{S\,N}^2}{l} \mu \frac{d i}{d t} = \mathrm{S\,N} \frac{d b}{d t} \quad \ldots\ldots \quad (4).$$

Again, since e is the instantaneous value of the impressed electromotive force it follows that at every instant

$$e = \mathrm{R}\, i + \mathrm{S\,N} \frac{d b}{d t} \quad \ldots\ldots\ldots \quad (5).$$

If the resistance of the copper circuit is very small then in practice it will nearly always happen that the magnitude of the resultant electromotive force, $\mathrm{R}\, i$, is very small compared with the electromotive force of self-induction, viz., $\mathrm{S\,N} \frac{d b}{d t}$. This will always be the case if the number of turns, N, of the wire wrapped in the core is considerable. Hence in general we may write (5)

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* One gauss is a unit of magnetic induction equal to 10^8 "lines of force," or C.-G.-S. units.

$$e = \mathrm{S\,N}\frac{db}{dt},$$

Hence from equation (4) it follows that

$$e = \frac{4\pi}{10^9}\,\frac{\mathrm{S\,N}^2}{l}\,\mu\,\frac{di}{dt};$$

but since $e = \mathrm{E}\sin pt$ we have

$$i = \frac{10^9 l\mathrm{E}}{4\pi \mathrm{S\,N}^2\mu}\int \sin pt\,dt \quad . \quad . \quad . \quad . \quad (6);$$

and hence the maximum value of i, which we may write I, is given by the equation,

$$\mathrm{I} = \frac{10^9 l\mathrm{E}}{8\pi^2 \mathrm{S\,N}^2 n\mu} \quad , \quad . \quad . \quad . \quad . \quad (7).$$

Before we can make any use of the above formula (7) we must have some notion of the value to be given to μ in the equation. It may be useful to put down here the values of μ obtained by Prof. Ewing for a very long, soft, and well-annealed iron wire, corresponding to certain values of the induction density in the wire. They are as follows :—

	The induction density (B) in C.-G.-S. measure.	Corresponding value of the permeability (μ) for good soft wrought iron.
Lines of force per square centimetre.	1,000	560
	2,000	880
	3,000	1,160
	4,000	1,400
	5,000	1,600
	6,000	1,800
	7,000	1,960
	8,000	2,120
	9,000	2,280
	10,000	2,350

If we apply the values of μ taken from the above table in conjunction with the equation (7) to calculate the maximum value of the primary current on open secondary circuit for any transformer of the closed magnetic circuit type, we shall generally, but not always, find that the so calculated value of the current is less than the observed value. In many cases, however, the formula will give us a fair approximation to the maximum value of the so-called magnetising current. Thus, for example, take the case of the small Westinghouse transformer employed in Ryan's experiment and referred to in § 1 of this chapter. The mean length (l) of the magnetic circuit is 31 centimetres, the cross section (S) 63 square centimetres, and the number of turns (N) of the primary circuit 675. The frequency (n) was 138, and the value of E, 1,400 volts. Insert these values in (7) and we have

$$I = \frac{10^9 \times 31 \times 1400}{8\,\pi^2 \times 63 \times (675)^2 \times 138 \times \mu} = \frac{139}{\mu} \quad . \quad . \quad (8).$$

The maximum value of the induction density was in this case nearly 4,000. Corresponding to $B = 4{,}000$, the static permeability of soft iron is 1,400. If we put $\mu = 1{,}400$ in (8) we have $I = \cdot 1$ ampere, whereas a reference to page 446 shows that the maximum value of the primary current on open secondary is ·21 ampere. The quality of the iron may, however, have been inferior. Moreover, the eddy current and hysteresis loss were in this case considerable. If we give μ the value of 700, then the calculated and observed values of I would agree. An examination of other cases, however, shows that this equation (7) will give a fair approximation to the observed current.

Mr. Evershed has given* the data of a 30 horse-power Goolden-Ravenshaw Transformer as follows:

Mean length of magnetic circuit	145 cms.
Cross-sectional area of the magnetic circuit	95 sq. cms.
Total volume of iron in core	13,700 c.c.
Frequency	70
Primary turns	680
Secondary turns	34
Primary volts	2,000
Secondary volts	100
Primary circuit resistance	·97 ohm.
Secondary circuit resistance	·003 ohm.
Thickness of core plates	·05 cm.
Full load output	22,400 watts.
Maximum value of the induction density during the cycle	10,000 C.-G.-S. units.
Maximum value of the primary E.M.F.	2,800 volts.

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[*] See the series of articles on "The Magnetic Circuit of Transformers" in *The Electrician* for February and March, 1891, Vol. XXVI.

Corresponding to $B=10,000$, we have $\mu=2,350$. Hence, substituting the proper values for this transformer in equation (7), we have

$$I=\frac{10^9\times 145\times 2800}{8\,\pi^2\times 95\times(680)^2\times 70\times 2350}=\cdot 7 \text{ ampere.}$$

Hence the maximum value of the magnetising current is ·7 ampere and the $\sqrt{\text{mean}^2}$ value should be nearly ·5 ampere. The actual value is given as half an ampere. In the case of a number of other closed circuit transformers, all of which are worked at an induction density of about 4,000 or 5,000 C.-G.-S. which have been examined by the author, the above rule gives a tolerable approximation to the observed magnetising current. In these cases it was found that by taking values for μ, about 200 less than those given by Ewing for the softest wrought iron, a very close approximation to the value of the open circuit current could be obtained. The rule must not be, however, applied indiscriminately, and is only valid for cases of closed circuit transformers, having cores of good soft iron well laminated, and for cases in which the magnetisation of the iron is not carried up over the "knee" of the magnetisation curve.

It could not be applied, for instance, in the case of a solid wrought or cast-iron core, for in this case the resulting calculated value of I would be very far below the real or observed value. Such a case is obviously not really that of an open circuit transformer at all, for the eddy currents set up in the core are true secondary currents of considerable magnitude.

The equation (7) may be reduced to another form by expressing the value of μ as a function of B. As the permeability μ varies with the induction B, we may express μ approximately as a function of B, of the form

$$\mu=\alpha\,\mathsf{B}^{\beta}\quad.\quad.\quad.\quad.\quad.\quad.\quad.\quad(8),$$

where α and β are constants. To find the values to be given to α and β we may proceed thus: Taking logarithms of both sides we have

$$\log\mu=\log\alpha+\beta\log\mathsf{B}\quad.\quad.\quad.\quad.\quad.\quad(9).$$

If we plot this curve, taking the values given by Ewing for μ and B, we find that it is approximately a straight line, and that we have very nearly

$$\alpha = 5{\cdot}6,\ \beta = \frac{2}{3},$$

and hence $$\mu = 5{\cdot}6\,\mathsf{B}^{\frac{2}{3}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (10).$$

Calculating by this formula values of μ, and comparing them with the observed, we find a fair general agreement, especially between $\mathsf{B} = 1{,}000$ and $\mathsf{B} = 6{,}000$.

B.	Observed value of μ.	Value calculated from equation $\mu = 5{\cdot}6\,\mathsf{B}^{\frac{2}{3}}$.
1,000	560	560
2,000	880	890
3,000	1,160	1,165
4,000	1,400	1,410
5,000	1,600	1,612
6,000	1,800	1,848
7,000	1,960	2,049
8,000	2,120	2,240
9,000	2,280	2,420
10,000	2,350	2,595

From $\mathsf{B} = 1{,}000$ to $\mathsf{B} = 5{,}000$ the constant α has exactly the value 5·6, but from 5,000 to 10,000 the observed and calculated values of μ agree better if we take $\alpha = 5{\cdot}3$.

If we take $\alpha = 5$ and $\mu = 5\,\mathsf{B}^{\frac{2}{3}}$, and insert this value of μ in equation (7), we can reduce it to another useful form for practical work.

For taking equation (1), page 512, viz.,

$$4\pi \frac{N}{l} \mu\, i = b \quad . \quad . \quad . \quad . \quad . \quad . \quad (11),$$

and putting $\mu = 5\,b^{\frac{2}{3}}$ we have

$$20\,\pi \frac{N}{l} i = b^{\frac{1}{3}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (12).$$

If we put I for the maximum value in amperes of the primary current of the transformer in open secondary circuit, and B for the maximum value of the corresponding maximum induction density in C.-G.-S. measure, and E for the maximum value of the impressed primary electromotive force, then we reduce the equation (12) to the form

$$\frac{44}{7}\frac{N}{l}I = B^{\frac{1}{3}} = \left(\frac{E \, . \, 10^8}{pSN}\right)^{\frac{1}{3}} \quad . \quad . \quad . \quad . \qquad (13),$$

and this last can be written

$$I = \frac{40\,l}{N}\left(\frac{E}{nSN}\right)^{\frac{1}{3}} \quad . \quad . \quad . \quad . \qquad (14).$$

From equation (14) we can deduce very approximately the maximum value, I, of the primary "magnetising current" of a transformer when we are given the maximum value E of the primary electromotive force, and the dimension, section S and mean length l of the magnetic circuit, the number of turns N of the primary coil, and the frequency n.

The above equation (14) is, like equation (7), only applicable to closed magnetic circuit transformers with good soft iron cores, well laminated, and in which the ohmic resistance of the wire circuit is insignificant in comparison with the impedance of that circuit. But under these circumstances, when eddy current loss is small, the formula (14) is useful for calculating the open circuit current both for transformers and for choking coils.

We shall now point out another means by which the magnetising current can be approximately predetermined if the total loss in the core is known.

If hysteresis and eddy current energy loss were entirely absent from the core, it is clear that the whole energy conveyed to the primary circuit of a transformer on open secondary must be simply dissipated in heating the copper of the primary circuit; and hence, if this copper loss is also small the actual power given to the transformer would be zero. Under these circumstances the phase of the primary currents would be very nearly 90° behind that of the impressed electromotive force. If an iron core so well laminated that eddy current is practically absent is employed, then it will still be the case that the instant of the maximum value of the periodic primary current will be coincident with the instant of zero primary electromotive force, even though the form of the primary current curve may be very different from that of a simple sine curve. This is true even though the magnetisation of the core is carried up very much above the "knee" of the magnetisation curve.

In Fig. 48 is shown the indicator diagram of a small choking coil, or transformer with no secondary circuit. The core was composed of fine iron wire No. 36 gauge in diameter, and it was one of the coils employed by Messrs. Fortenbaugh and Sawyer on the experiments described on page 481. The core consisted of fine iron wire wound up into a ring. The ring was wound over with insulated wire, and the choking coil so formed had an indicator diagram taken by Ryan's method. The dimensions and data were as follows:—

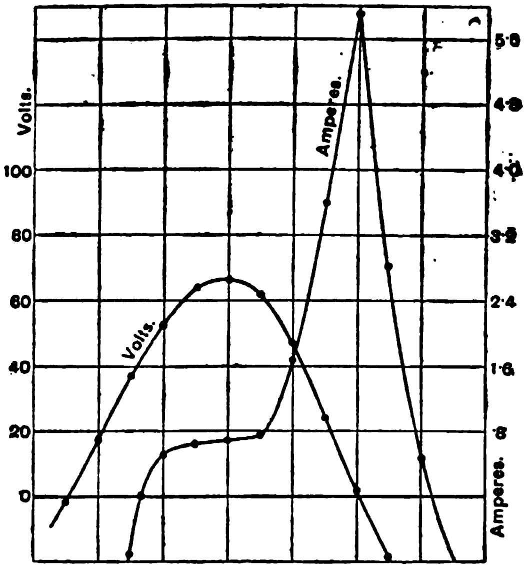

FIG. 48.

Indicator Diagram of Choking Coil, in which the induction is carried up to about 17,000 or 18,000 C.-G.-S. units.

Mean diameter of ring core	8·9 cm.
Area of cross section of core	3·14 sq. cm.
Mean length of magnetic circuit	26·5 cm.
Maximum induction density in core...	17,800 C.-G.-S.
Number of turns of wire..................	200
Resistance....................................	Negligible.
Frequency	92
Impressed E.M.F. maximum value...	65 volts.
Mean loss in the core	·33 watt per c.c.

In this fine wire core eddy current loss is practically absent at this frequency, and from the diagram it is seen that although the current curve is very far indeed from being a sine curve, yet its maximum value, of 5·9 amperes, happens at the instant of zero electromotive force. Another such diagram for a similar core is shown in Fig. 49. In this case the induction density is not carried up so high, but the same fact may be noted, viz., that the maximum value of the current happens at the instant of zero electromotive force. If we next consider the action of the eddy currents, we shall find that their presence in the core always causes the phase of the primary current to

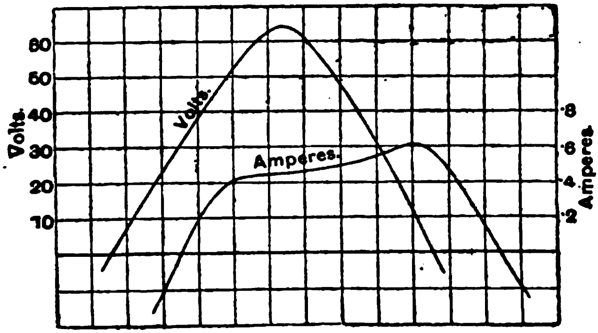

FIG. 49.

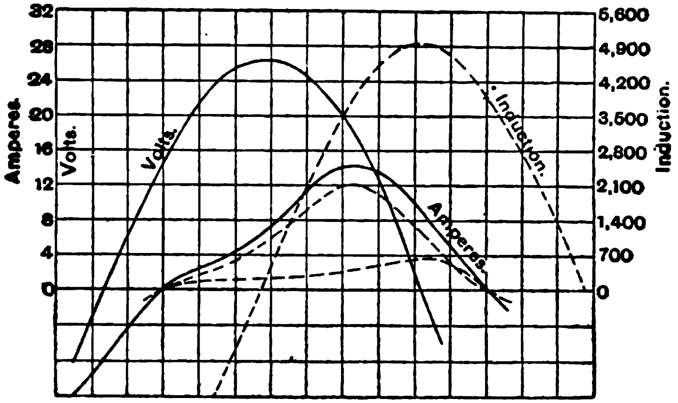

FIG. 50.

be advanced or brought back more into consonance with that of the impressed electromotive force.

The diagram in Fig. 50 is the indicator diagram of a choking coil composed of a solid cast-iron core wound over with 200

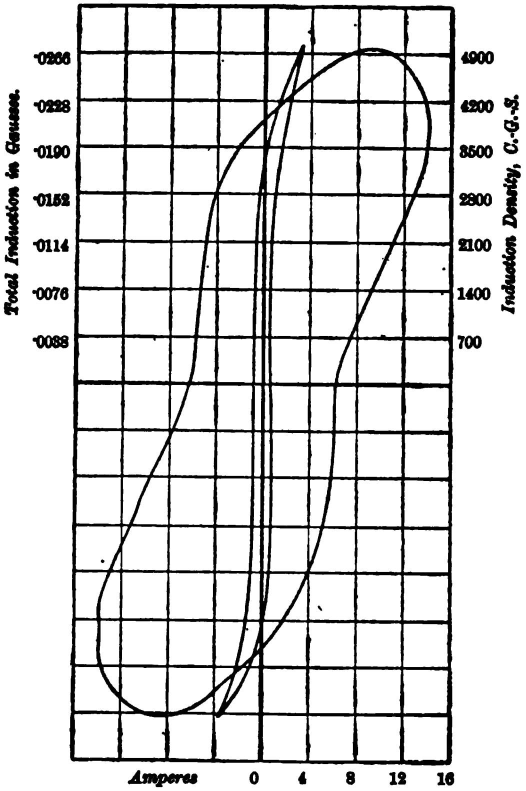

FIG. 51.

Diagram of Static Hysteresis (*Inner Curve*) and Total Loss (*Outer Curve*) for a Cast-Iron Ring. (Number of turns of wire in ring, 200; section of ring, 2·7 sq. cm.)

turns of wire of negligible resistance. The ring had a mean diameter of 8·6 centimetres, and a cross sectional area of 2·7 square centimetres. An alternating electromotive force having a frequency of 195 was applied to the circuit, and the diagram of current taken by Prof. Ryan. In this case the eddy current loss is very marked. From the observed value of the induction density B and the primary current (i), a diagram of core losses was formed (*see* Fig. 51), the outer curve being the (B, i) curve, and the inner curve the curve of static hysteresis deduced from separate observations. In the diagram in Fig. 51 the vertical divisions each represent 0·0038 of a gauss, and the horizontal ones each represent 4 amperes.

The whole area of the outer curve reckoned in gauss-amperes or joules is nearly ·8 joule, and this is, therefore, the whole energy wasted in the core in one complete magnetic cycle. Since the frequency is nearly 200 the whole loss of power in the core is nearly 160 watts. This experimental determination can be compared with a predetermination of the core loss. From the dimensions of the ring we find easily that the total volume of the iron is 73 cubic centimetres. The diameter of the cross section of the ring is $\sqrt{3{\cdot}44}$ centimetres. The maximum value of the impressed electromotive force was 26 volts, and that of the induction density 4,930 C.-G.-S. units. The frequency was 195.

The eddy current loss per cubic centimetre, as given by equation 7 on page 487, is $\frac{c\pi^2}{16} d^2 B^2 n^2 10^{-16}$ watts, where d is the diameter of the section in centimetres, and c is the specific conductivity of cast iron. For cast iron the value of $c\pi^2$ is very nearly 10^5. Hence we have the total loss in watts in the ring due to eddy currents equal to

$$73 \times \frac{10^5}{16} \times 3{\cdot}44 \left(\frac{195 \times 4950}{10^8}\right)^2 \text{ watts} = 144{\cdot}5 \text{ watts.}$$

The hysteresis loss by Steinmetz's law is equal to $\cdot 016\, n\, B^{1\cdot 6}\, 10^{-7}$ watts per cubic centimetre for cast iron, and hence the total hysteresis loss for the whole ring is

$$73 \times \frac{\cdot 16}{1{,}000} \times \frac{195}{10^7} (4{,}930)^{1\cdot 6} = 18{\cdot}5 \text{ watts.}$$

Therefore the total core loss by eddy currents and hysteresis is

$$144{\cdot}5 + 18{\cdot}5 = 163 \text{ watts,}$$

which agrees closely with the result of experiment.

The magnetic permeability of cast iron corresponding to an induction of 5,000 C.-G.-S. is nearly 200. If we attempt to calculate the current through the circuit when a periodic electromotive force, having a maximum of 26 volts, is applied to the coil, we shall find that we get a value far below the observed value. For if we insert in formula (7) the proper values, viz., $E=26$, $l=27$, $n=195$, $S=2{\cdot}7$, $N=200$, and $\mu=200$, we get

$$I=\frac{10^9\times 27\times 26}{8\times 9{\cdot}87\times 2{\cdot}7\times 200\times(200)^2\times 195}=2 \text{ amperes},$$

whereas the observed maximum value of the current is about 14 amperes. This is because the immense eddy current loss of 144 watts renders the choking coil virtually a transformer with a closed secondary circuit.

We shall now proceed to point out an empirical rule which will in nearly all cases enable the total core loss to be predicted when the so-called "magnetising current" is given, and *vice versâ*, provided that the iron circuit is a closed circuit, and that the iron is fairly well laminated. Under these circumstances we have shown that the total loss in the core can be calculated from the core dimensions and from the secondary electromotive force. If the reader will refer back to Fig. 13, p. 455, in which is shown the harmonic analysis of the primary current of a transformer on open secondary, he will see that the current curve can be analysed into a principal sine curve which lags one-eighth part of a phase behind the impressed electromotive force, and also into two smaller components. The principal sine curve has a maximum value a little less than that of the actual current curve. The mean power given to the transformer during one period is obtained by taking the mean of the values of the equally-spaced instantaneous currents and corresponding electromotive forces. It is quite evident that it is possible to so place a true sine curve of current with reference to the electromotive force curve that the mean power represented by this equivalent sine current is the same as that due to the actual current. It is also evident that a simple sine curve having the same maximum ordinate as the real current curve, but placed one-eighth part of a complete period in phase behind the impressed electromotive force curve, would, if it represented a current, be equivalent in mean power to the actual current. Let E be the maximum value of the electromotive force, and let it vary in a simple, periodic manner. Then $\frac{E}{\sqrt{2}}$ is the $\sqrt{\text{mean}^2}$ value of this electromotive force. It is the value which would be read on a Cardew voltmeter or dynamometer. In the same way if I is the maximum value of the equivalent simple periodic current of equal power value with the real current, $\frac{I}{\sqrt{2}}$ is its $\sqrt{\text{mean}^2}$ value. If θ is the angle of phase difference between E and I, and W is the true value of the power given by the currents I, we have seen (Vol. I.) that

$$\frac{E}{\sqrt{2}} \frac{I}{\sqrt{2}} \cos \theta = W.$$

It is convenient to call W the *real watts*, and the simple product of the $\sqrt{\text{mean}^2}$ values of E and I, viz.: the product $\frac{E}{\sqrt{2}} \cdot \frac{I}{\sqrt{2}}$ the *apparent watts.* The cosine of the angle of lag in this case is the ratio of real to apparent watts.* The apparent watts are the simple product of the volts as measured by a hot wire or Cardew voltmeter, and the current as measured by a Siemens dynamometer. In nearly all cases of closed iron circuit transformers with fairly well-laminated cores it will be found that the ratio of the real watts, or true mean power taken up in the core when the transformer is on open secondary circuit to the apparent watts, or product of the primary working volts and the magnetising current as read on the usual instruments, will be a number not far removed from 0·75, or somewhere between 0·7 and 0·8; that is to say, near to $\frac{1}{\sqrt{2}}$. This number is the cosine of 45°, and the rule in effect comes to this:—The real power taken up in the core is that which would be given to the transformer, if we suppose the magnetising current to be a simple sine curve current, and to lag about 45° behind the impressed electromotive force. In order to show that this is so, we shall compare the actual power taken up in the core (which includes, of course, any small loss in the primary circuit) of transformers on open secondary circuit with the product of the $\sqrt{\text{mean}^2}$ values of the primary electromotive force and the magnetising current, and show that the ratio is in all cases not far from $\frac{1}{\sqrt{2}} = 0{\cdot}707$.

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* When a current curve is a true sine curve, its *lag* with respect to another true sine curve representing electromotive force or current has a definite meaning. If it is not a true sine curve then the *lag* of its maximum value and of its zero value is not the same thing.

Transformer tested.	Primary volts. $\sqrt{\text{mean}^2}$ value $= \text{E}$.	Primary (magnetising) current. $\sqrt{\text{mean}^2}$ value $= \text{I}$.	*Real watts*, or true mean power taken up in the transformer (core) on open secondary circuit $= \text{W}$.	*Apparent watts*, or product of E & I, $= \text{W}^1$.	Ratio $\frac{\text{W}}{\text{W}^1} = \text{P}$. $=$ *power factor.*
Westinghouse 1 H.P.	1,000	0·14	95·7	140	0·68
Mordey ...... 8 H.P.	2,400	0·07	174	126	0·72
Stanley ...... 2 H.P.	1,000	0·053	37·5	53	0·707
Westinghouse 2 H.P.	1,000	0·061	48	61	0·79
Slattery ...... 2½ H.P.	1,000	0·056	45·5	56	0·81
National ...... 2½ H.P.	1,000	0·112	75·0	112	0·67

The results from many other closed magnetic circuit transformers tested are in the same direction, and show that for most ordinary types of well-laminated closed iron cores the relation between primary volts, magnetising current, and total loss in the transformer on open secondary circuit is expressible by the empirical formula

$$\textit{Primary volts} \times \textit{magnetising current} \times P = \left\{ \begin{array}{l} \textit{Total loss in watts} \\ \textit{in transformer.} \end{array} \right.$$

The volts and current values being the $\sqrt{\text{mean}^2}$ values or the dynamometer values; and the constant P having a value varying from about 0·7 to 0·8. P may be called the *power factor* of the current.

In cases where the eddy current loss is very large, as in the case of the cast-iron ring above mentioned, the *power factor* in the above formula is much more nearly unity than 0·7. Thus, for the cast-iron ring (Fig. 50, *ante*), the $\sqrt{\text{mean}^2}$ value of the current is 8·6 amperes, maximum value being 14 amperes. The $\sqrt{\text{mean}^2}$ value of the primary electromotive force is 18·5 volts, and $18{\cdot}5 \times 8{\cdot}6 = 159$. The apparent watts are therefore 159, whilst the real watts taken up were found to be 160. On the other hand, for open circuit transformers, when on open secondary circuit, the *power factor* is found to be much less than 0·7, often as low as 0·1.

A series of very instructive experiments on a simple form of 1 : 1 open circuit transformer were made by Mr. Robert Shand in 1891.* Mr. Shand employed a simple straight double helix of insulated wire. A tube was wound over with two equal circuits of insulated wire. The resistance of each circuit was approximately 0·25 ohm. The hollow cylinder on which they were wound had a length of 7 inches, and an opening through its centre 2 inches in diameter, into which iron cores of various kinds could be drawn. Arrangements were made by which alternating currents could be sent through one coil under a constant pressure of 100 volts and a secondary of various magnitudes drawn off from the secondary. By means of a non-inductive wattmeter the power supplied to the primary and that given out by the secondary was approximately measured. In the first experiment no iron core was used at all. In the second an iron wire core of the same length as the coils, viz., 7 inches, was put in. In the third an iron wire core nearly twice as long as the coils, viz., 13 inches, was used, and in the fourth, the ends of the last long core were bent out like a thistlehead radially, as in a Hedgehog Transformer.

The primary current found flowing when the secondary circuit was left open, under these various conditions, is shown in the table on p. 526, $\sqrt{\text{mean}^2}$ values of currents and volts being understood.

Considering these experiments as different cases of straight or open-circuit choking coils, we see how very different is the current flowing through the primary circuit under the same, or nearly the same, impressed alternating electromotive force. The last observation especially shows how considerably the open-circuit current is reduced by "Hedgehogging" the ends of the wires projecting beyond the ends of the coil. For the last case, which is a practical one, we see also that the power factor is only about 0·13, or something rather more than one fifth of that which it would be if the magnetic circuit were wholly of iron.

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* See *The Electrician*, Vol. XXVI., p. 675, April, 1891, also *Electrical World* of New York, 1891.

Primary electro-motive force in volts.	Primary current in amperes.	Power absorbed in watts in primary coil.	Remarks.
100	52	657	No iron core used. Primary circuit had a resistance of about 0·25 ohm.
104	16·5	108	Small iron core, 7in. long, inserted in bobbin. Core same length as coils. Maximum induction in centre of core = 23,000 C.-G.-S. per sq. cm.
104	14	86	Thicker core, 7in. long employed. Maximum induction = 14,000 C.-G.-S. per sq. cm. in centre of core.
100	7·3	45	Iron wire core, 13in. long. Induction = 6,300 C.-G.-S. in centre of core.
100	3·27	43	Same core as above, but wires at ends spread out radially. Induction in centre of core = 6,300 C.-G.-S.

The values of the primary and secondary quantities for this model Hedgehog Transformer for various primary currents were found to be as follows :—

Efficiency at Various Loads of 1 : 1 Hedgehog Transformer.

Primary electro-motive force in volts.	Primary currents in amperes.	Power given to primary in watts.	Secondary current in amperes.	Power given to external secondary circuit in watts.	Efficiency in per cents.
100	3·27	43	—	—	—
100	3·9	142	—	—	—
100	4·4	268	2·24	221	82·5
100	6·7	574	5·3	518	90·2
100	11·2	1,078	10·3	994	92·2
100	16·3	1,550	15·3	1,419	91·5

The remarkable fact about these figures, in so far as this method of measuring the power is trustworthy, is that they show a great decrease in the iron losses as the secondary load increases. For whereas when the secondary circuit is open the losses in the primary copper circuit are $(3{\cdot}27)^2 \times 0{\cdot}25 = 2{\cdot}5$

watts nearly, leaving about 40 watts for the iron; at full load the copper losses in primary and secondary together are $\{(16{\cdot}3)^2+15{\cdot}3)^2\}\times 0{\cdot}25=125$ watts nearly; and hence the loss in the iron is only $1550-1419-125=6$ watts.

For the last four observations in the table corresponding to steadily increasing secondary currents, we have the copper and iron losses as follows:—

Iron Core Losses of Model Hedgehog 1:1 Transformer.

Secondary currents in amperes.	Total copper losses in watts.	External secondary circuit losses in watts.	Iron core losses in watts.	Total power given to primary in watts.
2·24	6·1	221	41	268
5·3	18·2	518	38	572
10·3	57·9	994	26	1,078
15·3	125	1,419	6	1,550

In the above table a decreasing loss in the iron is apparently shown.

The general predetermination of the primary currents for a transformer of any form, open or closed magnetic circuit, on open secondary circuit, is, however, a difficult problem, and can hardly be said to be entirely solved.

§ 12. **Design of Transformers.—Full Specification.**—We may now pass on to consider the full specification for a transformer. Let it be required to design a transformer, say, for transforming W watts of electric power from a pressure of E_1 volts to one of E_2 volts. Required to find the sizes of wires and numbers of turns of the two circuits, and the size of the core and waste of energy in it, under the conditions that the maximum induction density in the core shall not exceed B C.-G.-S. units and the current density in the circuits not exceed 1,000 amperes per square inch. Let other limitations imposed be that the waste of energy in the copper shall not be more than 2 per cent. of the full load.

Since the transformation ratio and power are known we may take it that approximately the full-load primary current will be $\frac{W}{E_1}$ amperes, and the full-load secondary current a little less than $\frac{W}{E_2}$ amperes. Let I_1 be the $\sqrt{\text{mean}^2}$ value of the full load primary current and R_1 the resistance of the primary circuit, and let I_2 and R_2 be the same quantities for the secondary circuit. Furthermore, let N_1, N_2 be the number of turns of wire on these circuits, and L_1 L_2 the lengths, and σ_1, σ_2 the cross-sections of these wires.

At full load the total rate of dissipation of energy in the copper circuits is

$$I_1^2 R_1 + I_2^2 R_2 = K D.$$

But,

$$R_1 = \frac{\rho l_1}{\sigma_1} \qquad R_2 = \frac{\rho l_2}{\sigma_2}$$

where $\rho = \frac{16}{10^7}$ ohms, or is the specific resistance per cubic centimetre of copper at ordinary temperatures—that is, the resistance of one cubic centimetre in ohms across opposed faces. Substituting these values of R_1 and R_2, we have

$$D = \frac{I_1}{\sigma_1}\rho I_1 l_1 + \frac{I_2}{\sigma_2}\rho I_2 l_2 \quad . \; . \; . \; . \; . \quad (1)$$

Now $\frac{I_1}{\sigma_1}$ and $\frac{I_2}{\sigma_2}$ are the current densities in these wires. This current density ought not to exceed 1,500 amperes per square inch, or 240 amperes per square centimetre.

Put, therefore,

$$\frac{I_1}{\sigma_1} = \frac{I_2}{\sigma_2} = 240,$$

and we have

$$D = \frac{240 \times 16}{10^7}\{I_1 l_1 + I_2 l_2\} \quad . \; . \; . \; . \quad (2)$$

But in practice $I_1 l_1$ will always be nearly equal to $I_2 l_2$. Hence we arrive at

$$D = \frac{868}{10^6} I_1 l_1 \quad . \; . \; . \; . \; . \; . \quad (3)$$

therefore also and

$$\left.\begin{aligned} l_1 &= \frac{10^6 D}{868 I_1} \\ \sigma_1 &= \frac{I_1}{240} \\ R_1 &= \frac{16}{10^7} \cdot \frac{l_1}{\sigma_1} \end{aligned}\right\} \quad . \; . \; . \; . \; . \; . \; . \quad (4)$$

These last three equations give us the length, section, and resistance of the primary wire when we know the full load primary current and the total power, D, permitted to be dissipated in the copper circuits when the transformer is fully loaded.

For example, let us take the case of a 30 H.-P. closed-circuit transformer and find all the quantities.

The full load of the transformer is 30 H.-P. = 22,400 watts. Suppose, as most likely, that 300 watts, or say, 1·3 per cent. of the full load, is to be allowed to be wasted in the copper circuits at full load, and that the transformer is to be designed for converting from 2,000 volts to 100. Then the full load primary current I_1 is 12 amperes. Therefore we have

$$l_1 = \frac{10^6 \times \cdot 300}{868 \times 12} = 30{,}000 \text{ centimetres.}$$

$$\sigma = \frac{12}{240} = \cdot 05 \text{ square centimetre.}$$

$$R_1 = \frac{16}{10^7} \frac{l_1}{\sigma^1} = \cdot 96 \text{ ohm.}$$

This gives us the length, section, and resistance which the primary circuit ought to have. Having found the dimensions of the primary circuit, we may obtain approximately those of the secondary by the division of l_1 by the transformation ratio $\frac{E_1}{E_2}$ and multiplication of σ_1 by the same fraction. Thus for the above transformer, the length of the secondary will be 1,500 centimetres, and its section 1 square centimetre, and its resistance ·0024 ohm.

The next step is to find the dimensions of the magnetic circuit. These are easily found, thus:—The primary electromotive force is to have a $\sqrt{\text{mean}^2}$ value in volts equal to E_1. Hence, its maximum value is $\sqrt{2}\, E_1$. If the maximum value of the induction density is $\mathbf{B}$, and if S is the cross-section of the magnetic circuit, then the value of the quantity $p\, \mathbf{B}\, S\, N_1$ is always nearly equal numerically to $10^8 \sqrt{2}\, E_1$, where $p = 2\pi n$ and N_1 is the number of primary turns, and $\mathbf{B}$ is measured in C.-G.-S. units. Hence,

$$S\, N_1 = 10^8 \frac{\sqrt{2}\, E_1}{p\, \mathbf{B}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

If we suppose the cross-section of the magnetic circuit to be a square, whose side has a length $\sqrt{S}$, then, since l_1 is the length of the primary wire, we have, very nearly,

$$\frac{l_1}{4\sqrt{S}} = N_1 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

Therefore from (5) and (6)

$$\sqrt{S} = \frac{4\sqrt{2}\,E_1\,10^8}{p\,B\,l_1} \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

This gives us the area of cross-section of the magnetic circuit.

For instance, for the transformer referred to above, we have $E_1 = 2{,}000$, $B = 10{,}000$, $n = 70$, $p = 440$, and $l_1 = 30{,}000$.

$$\therefore \sqrt{S} = \frac{5{\cdot}66 \times 2000 \times 10^8}{440 \times 10000 \times 30000} = 9 \text{ centimetres nearly.}$$

Therefore, the magnetic circuit should have a cross-sectional area of 80 or 90 square centimetres.

To find the mean length of the magnetic circuit we must know the volume of the iron. This we can find at once if we know what total loss is to be allowed in the iron. For, supposing l to be the mean length of the magnetic circuit, then $S\,l$ is very nearly the volume of the iron, and if the total loss to be allowed in the iron is given and the maximum induction density, we can find the total volume of the iron which will permit this to be the case. We have seen (*see* page 493, equation 21) that we can calculate from the frequency, dimensions of iron bands, and the maximum induction density, the loss in watts per cubic centimetre in the core due to eddy currents and hysteresis. On applying this formula to real cases we find that the loss in laminated iron cores of the usual kind, worked at the usual induction densities, varies between one watt per 20 cubic centimetres of iron to one watt per 50 cubic centimetres of iron. This last is a liberal allowance. Hence, if we know the total loss in watts to be allowed in the transformer core and multiply this by 40 or 50, we shall have a good approximation to the volume of the iron necessary. If we take 50 cubic centimetres per watt we shall not be stinting the core of iron. In the present case, take 30 cubic centimetres per watt. In the case of the transformer considered, viz., a 22·4 unit one, we allowed 300 watts to be wasted in copper losses. Let 500 watts be decided upon as allowable for the iron losses. We have then to ask, what volume of iron will allow 0·033 watt to be wasted per cubic centimetre. Obviously,

$$\frac{500}{\cdot 033} = 15{,}000 \text{ cubic centimetres.}$$

Therefore, since the volume of the iron is S l,

$$S\,l = 15{,}000$$

and if S is taken as equal to about 90 square centimetres, we have

$$l = 166 \text{ centimetres nearly.}$$

Hence the mean length of the magnetic circuit must be 166 centimetres.

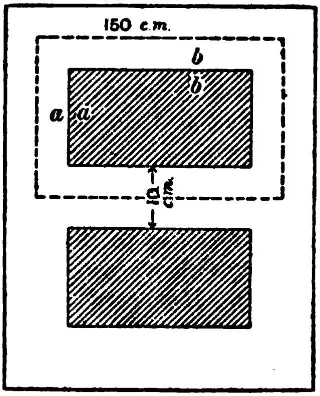

Fig. 52.—Diagram of Core Plate.

We can, therefore, draw the section of the iron core, or outline of the core plates. It will be as in Fig. 52. The central web must have a width of 10 centimetres, and the other dimensions must be so arranged that, whilst the apertures in the plate (shaded portions) have a maximum area, the length round the dotted line is not more than say 150 centimetres. It is obvious that, whilst still maintaining the necessary length of magnetic circuit, it is possible to vary the relative magnitudes of the sides *a* and *b* of the rectangular holes. But since all the wire to be wound on the transformer has got to be wound through these holes, it will be often necessary to so choose *a* and b that we get the maximum size of aperture in area consistent with maintaining the magnetic circuit length constant, and to do this by making a equal to b. We have then finally to know the number of turns of wire in each circuit.

Roughly speaking, this will be equal to $\frac{l}{4\sqrt{S}}$, where l is the length of the wire and $\sqrt{S}$ is the length of the side of the section of the magnetic circuit. If l is equal to 30,000 centimetres, as above found for the transformer in question, this rule gives us $N_1 = 750$ as the approximate number of primary turns, and hence $N_2 = 37$ as the approximate number of secondary turns.

We have found, then, the length, size, resistance, and number of turns of each circuit, and the dimensions of the magnetic circuit.

We can then calculate the relative volumes of iron and copper. Taking the case in consideration, we find the total volume of copper to be 3,000 cubic centimetres, and that of the iron 14,300 cubic centimetres. A little consideration will show that, since the wire on the coils has all to be wound through the aperture in the core, the limitation to the diminution of the core, and therefore to the loss in the iron, is to be found in the necessity for having a certain sized hole to get the wire wound through. If we calculate the area of copper exposed on cutting through the whole of the coils by a diametral cut in the case of the transformer considered, we shall find that it amounts to about 74 square centimetres, and even if we allow three times this area for insulation, there will still be abundance of room left in the aperture of 32 × 32 centimetres to get all the wire laid in. Hence in this case we could with advantage reduce the iron volume and waste less in the core. It would require further considerable discussion to show how the best dimensions of the core can be obtained. It may be pointed out, however, that the above rough sketch of a predetermination of the constants of a transformer shows that if we are given—

(1) The primary and secondary electromotive forces;

(2) The required output of the transformer;

(3) The amount or fraction of the energy so transformed to be wasted in the copper circuits;

(4) The amount of energy to be wasted in the iron circuit;

(5) The maximum induction density to be allowed;

(6) The frequency of the alternations; and thickness of core plates.

We can then calculate—

(1) The lengths, cross-sections, resistances, and number of turns of the primary and secondary circuits;

(2) The length and cross-section of the magnetic circuit;

(3) The waste in the transformer on open circuits;

(4) The approximate primary current on open secondary circuit.

(5) The "drop" in the secondary electromotive force as far as regards the loss in the copper of the secondary circuit.

The designer of a transformer has generally to steer a course between conflicting or opposing conditions of design. He may aim at obtaining some one definite result, or he may try to combine these different conditions so as to obtain the best all-round combination. He may design, for instance, for high efficiency at light loads, regardless of magnitude of magnetising current or of "drop;" or he may aim at a high maximum efficiency and small "secondary drop," and leave the all-day efficiency to take care of itself. Again, it is a distinct advantage in one way for the iron core of a transformer to get hot in working, because it blocks out eddy current loss by lowering the conductivity of the iron, but in another respect it may be very disastrous to the insulation for it so to do.

As far as regards minimising energy losses, the iron core should be run as hot and the copper as cool as possible, and an ideal transformer should therefore have the iron enclosed and the copper ventilated. In the smaller sizes of transformers the iron core losses will always be relatively greater than in larger ones. A transformer for 250 watts (5-light) can hardly be made to lose less than 20 watts in the core, but a 500-watt transformer can be made to lose not more than 25 watts, and a 2,000 watt not more than 45 watts. Hence, supposing that in each case the loss in the copper is 2 per cent., we shall find the full load efficiencies come out respectively 90, 95, and 95·7 per cent., larger sizes being similarly still more efficient.

With respect to magnetising current we have seen that for closed circuit transformers a large magnetising current means proportionate loss in the core. The magnetising current can be reduced by increasing the number of primary turns; but then the secondary turns, and hence the secondary ohmic drop, is likewise increased. The only way in which this last can be then also diminished is by increasing the section of the copper in the secondary circuit, and so again reducing the secondary resistance. This would involve, of course, an increase of cost. In the case of large sub-station transformers it may be worth while to incur this outlay to reduce the copper and iron losses to the lowest possible amount. These may be roughly taken at one watt per pound weight for the iron core, and between four and five watts per pound weight for the copper when the current density is taken at 1,500 amperes per square inch.

The best ratio of iron to copper loss can only be found by trial. Generally speaking, we may say that a high "all-day" efficiency cannot be obtained unless the iron losses are kept small. Hence some designers have sought for the solution of a high "all-day" efficiency by employing open iron circuit transformers. In so doing, however, they meet with another difficulty, viz., that they then encounter a large magnetising current. It is true that this current is a current having a small power factor, or is a "wattless" current when in the transformer; but it is not "wattless" in the mains and armature circuits, and a large "magnetising current" means, therefore, an increased loss in transmission, and a lowered plant efficiency. Condensers in parallel with the transformer have then been proposed as a means of extricating the open-circuit transformer from this difficulty. It is pretty clear, however, that all dielectrics possess some hysteresis, and Mr. Steinmetz has shown that this dielectric hysteresis increases as the square of the electromotive force. Hence, if this is the case, unless we can find a dielectric which will bear working at 1,000 or 2,000 volts with negligible hysteresis, it may happen that the energy loss is merely shifted from one place to the other, and that a closed iron circuit transformer with magnetic hysteresis and small magnetising current is as good or better than an open iron circuit tranformer with large "wattless" magnetising current, *plus* a condenser having some dielectric hysteresis working with it. We may avoid Scylla but fall upon

Charybdis. There is room for more investigation before these points are settled.

One of the most important matters to which the designer of transformers has to direct his attention is the proper and efficient lamination of the iron core of the transformer. In many existing types of commercial transformer the neglect of attention to this point greatly reduces the efficiency of the apparatus by permitting iron core losses of unnecessary magnitude to exist. Some approximate working formulæ have been given in Section 7 of this chapter, which enable the eddy current and hysteresis losses to be roughly determined for thin iron plates and wires.

A full and general investigation of the behaviour of iron to magnetising force has been made by Prof. J. J. Thomson,* which demonstrates in the most complete manner the necessity for very fine lamination in the iron plates or wire employed for transformer cores. Reference has already been made to the fact that when an alternating magnetising force is applied to an iron rod or plate the eddy currents set up in the superficial portions of the iron more or less screen the interior parts, and the induction in the iron is consequently unequally distributed. In fact, there is a complete analogy between the manner in which an alternating electromotive force applied to a conducting circuit creates a periodic current in a conductor and the manner in which an alternating magnetising force applied to a magnetic circuit creates magnetic induction in magnetisable material. For the electromotive force establishes a current of such kind that the amplitude of the wave, or maximum value of the current strength during the period, diminishes as we pass from the surface to the centre of the conductor, and moreover the phase of the current undergoes a retardation. At the surface the current strength is greatest, and at the centre of the conductor, if of sufficiently great diameter, and the frequency be great enough, the current strength may be practically zero. Quite similar is the distribution of magnetic induction under the influence of periodic magnetising force, and Prof. Thomson's equations permit us to calculate the gradually decreasing maximum induction density as we proceed from surface to centre of the iron. Hence, if the iron plate or wire is thick enough the central portions practically may not be magnetised at all under a periodic magnetising force, and, as Prof. Ewing has pointed out,[*] the result is that to obtain a given mean magnetic induction we have to increase the superficial magnetising force to a value greater than would be necessary if this screening did not occur.

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* See *The Electrician* for April 8, 1892, p. 599, Vol. XXVIII

This crowding of the induction to the superficial portions of the iron has the effect also of increasing the energy waste due to hysteresis proper, just as in the analogous case of the current distribution, the energy waste due to ohmic resistance is increased by the increase of real resistance of the conductor for a given total current strength when the frequency is so augmented as to create unequal distribution of the current over the cross-section of the conductor. When dealing with the case of alternate-current flow in conductors we have mentioned that this inequality in current density does not come into play practically for such a frequency as 100 ∿ unless the conductor has a diameter of at least 1 centimetre. Prof. Ewing has, however, shown that in the magnetic case a thickness of the iron plate or wire of even 2mm. is sufficient to cause the magnetic force at the central portions to be only one-eighth part of that which it is at the surface for the same frequency of 100 ∿. Hence for any thickness of wrought iron plate or wire of anything of this order there is a marked effect of magnetic screening. The magnetic force at the centre of a plate of wrought iron 1mm. thick is only 52 per cent. of that at the surface, maximum values being understood. In the case of a plate half a millimetre thick, the central force would be, however, 92 per cent. of the surface force. In a transformer core, what we require is a constant mean value of the induction, since it is upon this that the constant secondary electromotive force required depends. Moreover, the screening action operates to create a concentration of the induction at the surface of the iron, and this disposition of it aggravates the total hysteresis loss, which, as we have seen, varies at any point as the 1·6th power of the induction density.

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[*] See *The Electrician*, Vol. XXVIII., p. 631.

We must refer the reader to Prof. Ewing's paper (*loc. cit.*) for further information. The general result of these investigations, however, is to show that at a frequency of 100 ∿ an alternating magnetic force, applied to an iron plate or wire, produces only such an induction as would be equivalent to uniformly magnetising one-quarter of a millimetre in depth of the iron to the extent that the surface skin is magnetised; in other words, when the diameter of the plate or wire exceeds one-half millimetre, screening effects begin to make themselves felt. The curves in Fig. 53 represent the results of some calculations made by Prof. Ewing of the eddy current and hysteresis losses in iron plates of given dimensions. It will be found that these do not much differ from the approximate formulæ given in Section 7, for cases in which we consider plates of less than 1mm. in diameter.

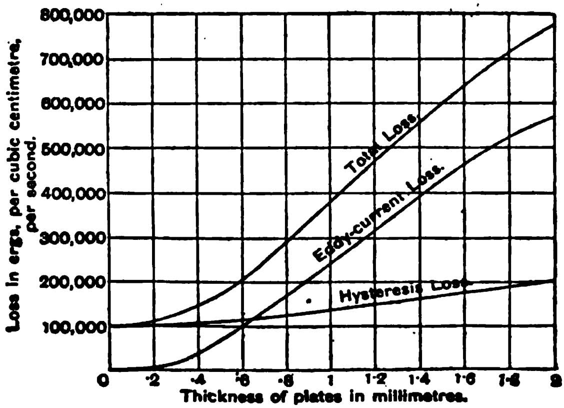

FIG. 53.

Curves representing the hysteresis and eddy current losses in wrought-iron plates of various thicknesses. Frequency = 100 ∿. B = 4,000. (Ewing.)

The moral of all the above is that the lamination of the iron plates forming the core of the transformer should be effectually carried out. To get good results the core plates should not be more than 10 or 12 mils, or 0·01 of an inch, in thickness, and be lightly painted over with oxide paint on one side. By so doing the deleterious results of eddy current loss and augmented hysteresis loss can be avoided, the total loss in the iron being reduced to about one watt per 80 cubic centimetres of core when a frequency of 100 is used, and a maximum mean induction density of 4,000 employed. In this case, with plates of 0·25mm., or 10 mils, in thickness, the eddy current loss would be about one-seventh part of the hysteresis loss, and one-eighth part of the whole core loss.

It is shown in Prof. J. J. Thomson's Paper, to which we refer the reader, that if a slab of iron of given thickness is divided up into laminæ, and then subjected to alternating magnetising force, that the loss of energy in the whole slab by eddy currents is inversely proportional to the square of the number of laminæ. Thus, in building up a transformer core, if the iron plates or bands are made of iron one-half millimetre thick (=0·02in.), the eddy-current loss will only be one quarter of that which it would be if the bands or plates are made one millimetre thick. The mathematical investigation shows that lamination is very little use if the plates or bands are more than one millimetre thick.

The purer the iron, that is, the greater the conductivity and hence also the greater the permeability, the greater must be the lamination. Increased frequency demands also a greater proportional degree of lamination. Conversely it follows that when we are dealing with cast-iron, of which the conductivity is only about one-tenth that of the purest wrought iron, and in which the permeability at a given induction is also only one-tenth, the shielding effect is not nearly so pronounced. In the case of cast iron a rod one centimetre in diameter exposed to an alternating magnetising force would not experience anything like the inequality of distribution of induction over its cross-section which would be manifested by a rod of wrought iron of equal cross-section exposed to the same magnetising force. The worse specific conductivity of the cast iron causes it to exercise a less degrading effect upon the wave of magnetising force, which therefore penetrates further into the metal without being reduced in amplitude and delayed in phase, as it is when advancing into the better conducting and more permeable wrought iron.

§ **13. Determination of Magnetic Leakage.**—One quantity we have not yet determined by our calculations, and that is the "drop" in the volts on the secondary terminals of the transformer due to magnetic leakage. The total "drop" or fall of electromotive force between no load and full load on the secondary circuit is of course made up of "drop" due to copper loss, or C^2R loss in the secondary circuit, and drop due to leakage of induction. The total "drop" should not exceed four or five per cent. in small transformers and two per cent. in large transformers. It is a difficult matter to predetermine the value of that part of the secondary "drop" due to magnetic leakage. Most makers have arrived at a minimum leakage drop for their own particular form of transformer by processes of trial and failure. Magnetic leakage is not nullified even when a primary coil is overlaid by and sandwiched in between two secondary coils; if there is a space between the coils, for in this case the reverse magnetising effect of the secondary currents partly drives the induction, due to the primary circuit, out of the iron into the space between the primary and secondary coils.

The effect of an assumed percentage of magnetic leakage may, however, be calculated. If N_1 and N_2 are the numbers of turns of wire in the primary and secondary circuit of the transformer, and if μ is the mean value of the permeability corresponding to the maximum induction employed, and if S is the section of the magnetic circuit and l its length, then we can easily see that the mean value of the self-induction L of the primary circuit is given by the equation,

$$L = \frac{4\pi}{10} \frac{1}{10^8} \frac{\mu}{l} S N_1^2,$$

and accordingly the mean value of the self-induction N of the secondary circuit is given by

$$N = \frac{4\pi}{10} \frac{1}{10^8} \frac{\mu}{l} S N_2^2.$$

The mutual induction M of the two circuits, on the assumption that there is no magnetic leakage, or that every line of force linked with the primary is also linked with the secondary, is therefore

$$M = \sqrt{LN} = \frac{4\pi}{10}\frac{1}{10^8}\frac{\mu}{l} S N_1 N_2.$$

Suppose, however, that M is not equal to $\sqrt{LN}$, but is expressed by

$$N = \sqrt{LN}\,(1 - x),$$

where x is a fraction less than unity expressed as a percentage.

Then x is the magnetic leakage expressed as a percentage. This definition of magnetic leakage as a measurable quantity has been given by Prof. J. Perry.* This definition of the magnetic leakage makes it dependent on the ratio of the mean value of M to $\sqrt{LN}$. It is, of course, easy to object that the coefficient of self and neutral induction in a transformer must be variable quantities; but we have shown above that the iron behaves throughout the magnetic cycle as if it had a constant average magnetic permeability, which is a simple function of the maximum induction density during the period; and accordingly the L, M, and N in the above formula have perfectly definite values, and may be called the mean coefficients of self and mutual induction.†

Starting with this assumption of a mean constant permeability in the transformer core, Prof. Perry (*loc. cit.*) has calculated many interesting tables for transformers of certain data, giving the currents, lags, electromotive forces, efficiencies, &c., for various secondary currents, for details of which we must refer the reader to the original Paper. In particular he has calculated the effect of certain assumed magnetic leakages of 1, 5, 10 per cent., &c., and shown that the effect of magnetic leakage, which is, of course, most apparent when the external resistance of the secondary circuit is as much reduced as possible, is

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* See "A Study of Transformers," *Phil. Mag.*, August, 1891, p. 168; also, "A Method of Measuring Power in Transformers," *Phil. Mag.* August, 1891, p. 191.

† We have seen that in the case of closed iron circuits well laminated, the value of μ in the equation above may be approximately taken as that corresponding to the maximum value of the induction in the core. In the case of open iron circuits or straight cores, when the magnetic circuit is partly iron and partly air, the value of μ is very much less. For a straight iron core of a bundle of iron wire, say eight or ten times as long as it is wide, the mean (air-iron) value of μ may be as low as 50. A straight iron core is in this respect like a dynamo field magnet with an enormous air gap.

(i.) To cause the primary current at full secondary load to lag behind the primary impressed electromotive force curve, in extreme cases by nearly 90deg.

(ii.) To cause the primary and secondary currents at full load to have much less mean values than they would have if leakage were absent.

(iii.) To create a much greater "drop" in the secondary terminal volts between full load and no load than would exist if magnetic leakage was absent.

Magnetic leakage apparently does not affect the difference of phase of the primary and secondary currents, which always tends to become 180° or thereabouts as the transformer is loaded up by reducing the resistance of the secondary external circuit.

§ **14. The Measurement of the Efficiency of Transformers.**—The practical determination of the various energy losses in a transformer and of its efficiency of transformation is a matter of considerable importance. It is not by any means, unfortunately, an easy thing; and those who have paid attention to it are not entirely in accord as to the best means by which it can be effected. Broadly speaking, there may be said to be six different electrical methods by which we may determine the power given to a transformer or the rate at which energy is delivered to it, and by which, therefore, its efficiency as an energy-transforming device may be determined. These are as follows:—(i.) calorimetric methods, (ii.) dynamometric methods, (iii.) voltmeter and electrometer methods, (iv.) ammeter methods, (v.) wattmeter methods, and (vi.) geometrical methods depending upon a knowledge of the form of the current and electromotive force curves of the transformer.

The need for special methods of measuring power given to an inductive circuit such as the primary circuit of a transformer, arises from the fact that when electrical power is being expended on an inductive circuit, the product of the $\sqrt{\text{mean}^2}$ value of the current flowing through that circuit and the $\sqrt{\text{mean}^2}$ value of the difference of potential between its ends does not give us any measure of the true power being expended on that circuit.

Calorimetric Methods.—In the calorimetric methods no attempt is made to measure the power actually given to the transformer, but a sum total is obtained representing all the various withdrawals of energy from the transformer when a stationary temperature has been reached. In carrying out a calorimetric investigation the transformer to be examined is enclosed in a light watertight metal box. The primary and secondary leads are brought through stuffing boxes or glands, or simply through india-rubber corks, in such way that whilst enabling the primary and secondary circuits to be electrically accessible the whole transformer is shut up in this watertight box. This box is then placed concentrically in another metal box of somewhat larger size, also closed watertight, and having two openings at opposite sides, one by which water can flow in and the other by which it can flow out. Arrangements are made by which a steady stream of water can be caused to flow through the space between the boxes and the temperature of the incoming and outgoing streams exactly measured by means of accurate and sensitive thermometers. The outer box or calorimeter should be supported by strings so as not to touch any other object. The so enclosed transformer must then have its secondary circuit connected to incandescent lamps or other practically non-inductive energy wasters, and the secondary current and potential difference at the secondary terminals of the transformer measured by means of a standardised ammeter and voltmeter. Such being the arrangements, a primary current is supplied to the transformer at the proper volts, and the water allowed to flow regularly through the calorimeter. At the end of a certain time the temperature of the whole apparatus will have become stationary. The water will enter at one side at a temperature, t°, and leave it on the other side at a higher temperature, t'^0, and energy will be given up to the external secondary circuit at a certain rate. The whole of the power which is being dissipated in the iron core of the transformer and that dissipated in the copper circuits is converted into heat and carried away by the water. Hence, if we measure the rate at which the water flows through the calorimeter when the stationary temperature is attained, and know the temperature at entrance and exit, we know what amount of energy is being carried off by the water. If G grammes of water flow through the calorimeter every second and if this water is raised from t° to t'° then G $(t'-t)$ units of heat are carried off every second; since one gramme centigrade unit of heat is very nearly equal to 4·2 joules. Hence the rate of removal of energy by the water is equal to 4·2 G $(t'-t)$ watts. If A is the amperes in the secondary circuit and V the secondary terminal volts, the rate of removal of energy by the secondary circuit is AV watts. Hence, since the temperatures are stationary the rate of supply of energy to the transformer must be equal to the total rate of loss; or the power, W, in watts given to the transformer must be such that

$$W = 4{\cdot}2\,G\,(t'-t) + AV.$$

Hence the efficiency of transformation ϵ is

$$\epsilon = \frac{AV}{4{\cdot}2\,G\,(t'-t) + AV}.$$

In accurate experiments a small correction would have to be applied for the energy lost by radiation from the calorimeter; but this would not usually be large. The special difficulties attending the experiment are the measurement with sufficient accuracy of the temperatures of the incoming and outgoing water. It is probable that the best way of doing this would be by a pair of thermo-electric junctions, placed in the incoming and outgoing currents.

Experiments of this kind have been made by Prof. Roiti in Florence and by Prof. Ayrton. The method itself was originally suggested by Dr. Louis Duncan.* There are many difficulties connected with the employment of this calorimetric method, and observers were led to employ it chiefly at a time when no better method was known.

Mr. Mordey has a practical workshop modification of this method, which deserves mention. He passes a primary current into a transformer, and allows it to come to its steady temperature. When this is known to be the case by a thermometer placed in the interior or on the core, the alternating current is switched off and a continuous current is supplied to the primary coil, which has its strength so adjusted that the temperature of the transformer is kept up to the before-attained constant temperature. The power supplied by this constant current (which is easily measured) is assumed to be the same as that given to the transformer by the alternating current after deducting the amounts given off by the secondary circuit, if any.

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* *Electrical Review*, London, July 29, 1887, Vol. XXI., p. 116; see also *Journal of the Society of Telegraph Engineers of London*, Vol. XVII., 1888 p. 168.

The assumption made is that, since the transformer has attained a constant temperature, the loss of energy by radiation must balance the gain of energy from the primary circuit after deducting the amount given off by the secondary circuit; and that, therefore, if we keep up the equilibrium by substituting a continuous for an alternating current, the energy loss, and therefore the energy supply, must be the same. One objection that has been urged against this process is that in the case of the alternating current the seat of the chief generation of heat is in the iron core; whilst in the case of the continuous current it is wholly in the copper circuit, and therefore that it does not follow that the same rate of absorption of energy will in both cases be required to keep up the same surface temperature of the transformer. The objection may not be a valid one, but it has been presented.

Dynamometric Methods.—In these methods the electro-dynamometer is employed as an electrical power meter. These methods were first introduced by Mr. Blakesley, and have been chiefly developed by him. In an electro-dynamometer such as that of Siemens there are two electric circuits, one fixed and the other movable. If two alternating electric currents of equal period, from different, or the same, sources are passed through these circuits, and *if the time of free oscillation of the movable circuit is very large* compared with the time of a complete period of the alternating currents, then the force required to hold the movable circuit in a fixed position with reference to the other circuit is proportional to the average or mean of the values of the products of the fluctuating current strengths in each circuit; such values being taken at equidistant and numerous instants during the complete period. If one and the same periodic current is passed through both circuits, then the force is proportional to the mean of the squares of the equidistant instantaneous current values. In most cases the force employed to balance the electro-dynamic force between the circuits is that produced by the torsion of a spring. Supposing that the free and unconstrained position of the movable circuit is such that its plane is perpendicular to that of the fixed circuit, we shall call this position the zero position of the movable circuit. If the action of the electrical forces is to produce a twist or torque on the movable circuit, and we apply an equal and opposite torque to restore it to its zero position, we shall call this the *restoring couple.* If the same current flows through both circuits, the restoring couple is proportional to the mean of the squares of the values of the equidistant instantaneous current strengths during the complete period. If different currents of the same frequency flow in the two circuits, the restoring couple is proportional to the mean of the product of the simultaneous instantaneous equidistant current values taken throughout the period. The first case is called the *dynamometer* reading. The second case is called the *split dynamometer* reading. We shall suppose that in all cases the dynamometer has been calibrated by means of a continuous current, so that if we have a dynamometer reading a corresponding to a steady or continuous current I passed through the instrument, then when an alternating current is passed through it the dynamometer reading a indicates a current of which the $\sqrt{\text{mean}^2}$ value is I. More precisely, if i is the instantaneous value of a periodic current of which T is the periodic time, then the dynamometer reading gives us the value of the integral

$$\frac{1}{\mathrm{T}}\int_0^{\mathrm{T}} i^2 \, dt,$$

or the mean of the squares of the instantaneous values of the current during the complete period. If i_1 and i_2 are the instantaneous values of the equiperiodic currents sent through a split dynamometer, then the reading of the dynamometer gives us the value of the integral

$$\frac{1}{\mathrm{T}}\int_0^{\mathrm{T}} i_1 i_2 \, dt,$$

or the mean of the product of the instantaneous values of the two currents during the period.

Let us see what these integrals become in certain special cases. Consider simple periodic currents, that is, let

$$i = \mathrm{I} \sin p\, t,$$

where $p = \frac{2\pi}{\mathrm{T}}$; then

$$\frac{1}{\mathrm{T}}\int_0^{\mathrm{T}} i^2\, d\, t = \frac{\mathrm{I}^2}{\mathrm{T}}\int_0^{\mathrm{T}} \sin^2 p\, t\, dt,$$

$$= \frac{\mathrm{I}^2}{\mathrm{T}}\int_0^{\mathrm{T}} \frac{1 - \cos 2\, pt}{2}\, dt,$$

$$= \frac{\mathrm{I}^2}{2}.$$

The dynamometer reading is proportional to half the square of the maximum value of the current. Again, if we consider two simple equiperiodic currents, i_1 and i_2, one retarded behind the other by an angle of lag θ, so that

$$i_1 = \mathrm{I}_1 \sin p\, t,$$

and

$$i_2 = \mathrm{I}_2 \sin (p\, t - \theta),$$

then the split dynamometer reading is proportional to

$$\frac{1}{\mathrm{T}}\int_0^{\mathrm{T}} i_1\, i_2\, d\, t = \frac{\mathrm{I}_1 \mathrm{I}_2}{\mathrm{T}}\int_0^{\mathrm{T}} \sin p\, t \sin (p\, t - \theta)\, d\, t,$$

$$= \frac{\mathrm{I}_1 \mathrm{I}_2}{\mathrm{T}}\int_0^{\mathrm{T}} (\sin^2 pt \cos \theta - \sin pt \cos pt \sin \theta)\, dt,$$

$$= \frac{\mathrm{I}_1 \mathrm{I}_2}{2} \cos \theta.$$

The split dynamometer reading is proportional to the product of the cosine of the lag and half the product of the maximum value of the currents.

Hence, if the two currents are simply periodic, but lag one behind the other, and we pass the currents separately through dynamometers to get the dynamometer reading for each, and then pass them jointly through a split dynamometer; and if we then get instrumental readings, α, β, and γ, such that

$$\alpha = \frac{\mathrm{I}_1^2}{2},$$

$$\beta = \frac{\mathrm{I}_2^2}{2},$$

$$\gamma = \frac{\mathrm{I}_1 \mathrm{I}_2}{2} \cos \theta,$$

assuming the constant of each instrument to be unity, or that it reads direct, we can obtain the value of cos θ, for

$$\cos\theta = \frac{\gamma}{\sqrt{\alpha\beta}}.$$

We can thus determine the angle of lag of the simple periodic current I_2 behind the current I_1. This method of using the dynamometer is due to Mr. Blakesley. Mr. Blakesley has employed this split dynamometer method for many purposes, but the one which most concerns us here is his ingenious method of using the dynamometer to determine the efficiency of a transformer. For this he employs three dynamometers, D_1, D_2, D_3. Two of them, D_1 and D_2, are put as current measurers in the primary and secondary circuits, and one, D_3, used as a split dynamometer, takes current from the primary circuit through one coil, and from the secondary circuit through the other, the three being arranged as in Fig. 54. Let us suppose the dynamometers to be direct reading, so that the reading on the torsion head of the dynamometer gives directly the mean value of the square of the instantaneous current through it when used as a simple dynamometer, and the mean product of the separate currents when used as a split dynamometer. The readings giving thus the mean of the squares of the instantaneous values of the currents, or the mean of the products of the instantaneous values of the currents, as the case may be. We proceed to give Prof. Ayrton's and Mr. Taylor's general proof of Mr. Blakesley's rule for deducing the mean value of the power taken up in the transformer.*

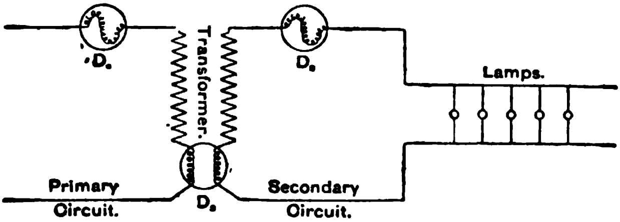

FIG. 54.

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* See *Phil. Mag.*, April, 1891, p. 354, "Proof of the Generality of certain Formula published for a Special Case," by Mr. Blakesley.

Let N_1 and N_2 be, as usual, the number of the primary and secondary turns on the transformer. Let e_1 be the primary impressed electromotive force at any instant, let i_1 and i_2 be the corresponding instantaneous values of the primary and secondary currents, and b the value of the mean induction density in the core. Take R and S for the resistances of the primary and secondary circuits. Then as usual,

$$e_1 = R i + \frac{1}{10^8} N_1 \frac{db}{dt}.$$

Also *if* the induction through the secondary is equal to $N_2 b$ at the instant when that through the primary is $N_1 b$, then, and *then only*, we have also

$$S i_2 = \frac{1}{10^8} N_2 \frac{db}{dt};$$

therefore

$$e_1 = R i_1 + \frac{N_1}{N_2} S i_2,$$

and

$$e_1 i_1 = R i_1^2 + \frac{N_1}{N_2} S i_2 i_1.$$

If T is the periodic time, it follows from this last equation that

$$\frac{1}{T}\int_0^T e_1 i_1 \, dt = \frac{R}{T}\int_0^T i_1^2 \, dt + \frac{N_1}{N_2}\frac{S}{T}\int_0^T i_1 i_2 \, dt.$$

The first term of this last equation is the value of the mean power or mean watts given to the primary circuit. Call this W_1. The second integral is R times the square of the dynamometer reading for the primary current. Call this RD_p. The value of the third integral is $\frac{N_1}{N_2} S$ times value of the split dynamometer reading, which gives us a reading we will call $\frac{N_1}{N_2} S D_{ps}$. Therefore,

$$W_1 = R D_p + \frac{N_1}{N_2} S D_{ps}.$$

Hence having the power in watts given to the primary coil, we can easily find the efficiency when we know the power in watts given to the external secondary circuit. If I_2 is the $\sqrt{\text{mean}^2}$ value of the secondary current, and V_2 is the $\sqrt{\text{mean}^2}$ value of the potential difference between the secondary terminals of the transformer, then the power in watts spent in heating the secondary coil in the transformer is $S I_2^2$, and the power in watts given to the external secondary circuitis $I_2 V_2$. Hence, the efficiency ϵ is

$$\epsilon = \frac{I_2 V_2}{R D_p + \frac{N_1}{N_2} S D_p} ;$$

or if S^1 is the resistance of the external secondary circuit, and D_s is the dynamometer reading of the instrument in the secondary circuit, then

$$\epsilon = \frac{S_1 D_s}{R D_p + \frac{N_1}{N_2} S D_p} .$$

The above proof makes no assumption that the current follows a simple sine curve law. It is perfectly general. It does, however, assume that there is no magnetic leakage. As in every transformer on *full* load the number of lines of induction linked with the primary and secondary circuit is not the same at the same instant, it follows that some degree of caution should be exercised in applying this formula in practice. The method also fails when applied to a transformer or open secondary circuit, because obviously then the split dynamometer gives no reading.

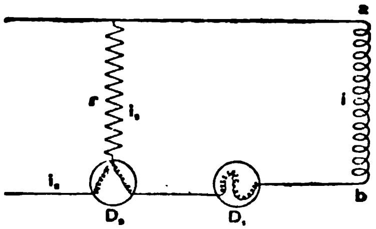

FIG. 55.

Mr. Blakesley made known, however, in 1891,* a perfectly general method of employing a split dynamometer to measure the power taken up in any inductive circuit, making at the same time no assumption as to the form of the current curve. The method makes use of a dynamometer D_1 or ammeter, a split dynamometer D_2 and a non-inductive resistance r (*see* Fig. 55). Let $a\ b$ be the inductive circuit, in which the power is to be measured. Let i be the current in it at any instant, and let i_1 be the current in the non-inductive resistance, and i_2 that in the line. Then the coils of the split dynamometer are traversed by the current i_2 and i, and the reading of D_2 measures therefore the mean of the product $i_2\,i$. Also the dynamometer D_1, measures the mean value of i^2. But we have always, at every instant,

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* See *Phil. Mag.*, April, 1891, p. 346.

$$\begin{aligned} i\,i_1 &= i\,(i_2 - i) \\ &= i\,i_2 - i^2 \\ \therefore\quad r\,i_1\,i &= r\,(i\,i_2 - i^2) \end{aligned}$$

but $r\,i_1 i$ is equal to the instantaneous value of the power taken up in the inductive circuit $a\,b$. Hence if the dynamometers

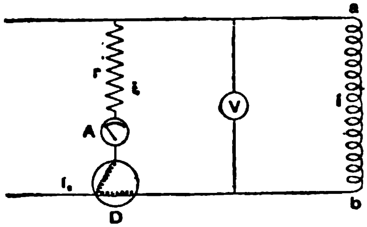

FIG. 56.

are graduated to read direct, and we call D_2 and D_1 the readings, and W the mean power taken up in $a\,b$, then we have, by taking mean values through a period,

$$\frac{1}{T}\int_0^T r\,i_1\,i\,dt = \frac{1}{T}\int_0^T r\,i\,i_2\,dt - \frac{1}{T}\int_0^T r\,i^2\,dt,$$

or

$$W = r(D_2 - D_1).$$

This method has the advantage of making no assumption as to form of current curves or absence of magnetic leakage. The reader is referred to Mr. Blakesley's Paper for other similar methods.

One other similar method may be mentioned. It was given by Mr. Blakesley in his Paper in 1891, but as a matter of fact was independently devised by Mr. A. Wright, and shown to the author, though not published, some time previously. A split dynamometer and ammeter are arranged as shown in Fig. 56, having a non-inductive resistance r

in series with the ammeter. If r consists, as it may be, of water resistance or incandescence lamps, then a voltmeter V is needed as well arranged across the mains. If i is the current in the inductive resistance and i_1 that through the ammeter, and i_2 that flowing into the split dynamometer, then the dynamometer (reading D) measures the mean value of $i_1 i_2$ and the ammeter reading A measures the $\sqrt{\text{mean}^2}$ value of i_1^2. If we call D the reading of the split dynamometer, and A that of the ammeter, then the mean power W taken up in the inductive resistance is given by the equation

$$W = r\,(D - A^2),$$

for the instantaneous value of the power given to the circuit $a\,b$ is $r\,i\,i_1$, and this is equal to $r\,(i_1 i_2 - i_1^2)$ or to $r\,i_1\,(i_2 - i_1)$. Whence the above formula follows. If r is not known, or is variable, then we must obtain its value by taking the $\sqrt{\text{mean}^2}$ voltmeter value, namely V, and dividing it by the $\sqrt{\text{mean}^2}$ current value A, and obtain the value of W from the equation

$$W = \frac{V}{A}\,(D - A^2).$$

This method has not always, however, the accuracy of the one before mentioned, because of the presence of an ammeter, which may have some self-induction, in a circuit r which ought to be quite non-inductive.

Electrostatic Voltmeter and Electrometer Methods.—In 1881, Prof. Ayrton, Prof. Fitzgerald, and M. Potier proposed a method of measuring the mean power given to an inductive circuit dependent on the use of a quadrant electrometer. At the time when this method was proposed, it was assumed that every quadrant electrometer obeyed a certain text-book law which may thus be stated. Suppose that the potential of one pair of quadrants, at any instant, is v_1, and that of the opposite quadrants v_2, and that of the needle v, then if the quadrants enclose, as usual, the needle, the electrical force on the needle deflecting it has been usually taken as expressed in all cases by the law

$$F = K\,(v_1 - v_2)\left\{v - \frac{v_1 + v_2}{2}\right\}$$

where F is the deflexional force on the needle, and K is an instrumental constant; and hence that the deflection of the needle when small followed the same law.

If we assume this to be the true law of the instrument, it can be shown that the mean power taken up in an inductive circuit can be measured as follows:—

Let AB be the inductive circuit, and let BC be a non-inductive resistance R in series with it. Let an alternating current flow through the two, and let v_a, v_b, v_c be the potentials of the points A, B, and C at any instant. The pairs of opposite quadrants of the electrometer are joined to the points A and B, and two observations are taken, one when the needle is joined to B, and one when it is joined to C. If then F_1 and F_2 are the forces on the needle, in each case we have

$$F = K \; (v_a - v_b \left\{ v_b - \frac{v_a + v_b}{2} \right\}$$

$$F = K \; (v_a - v_b \left\{ v_c - \frac{v_a + v_b}{2} \right\}$$

Subtracting we have

$$F_1 - F_2 = K \; (v_a - v_b) \; (v_b - v_c),$$

Hence, if the time of vibration of the needle is very large compared with the periodic time of the currents, the difference of the deflections of the needle in the two cases is proportional to the mean value of the product of the differences between the instantaneous values of the potentials at A and B and those at B and C. But, $(v_a - v_b)$ is the potential difference of the ends of the inductive resistance, and $(v_b - v_c)$ is proportional to the current flowing through it, because $\frac{v_b - v_c}{R}$ is the current in the non-inductive resistance in series with it. Hence, the difference of the two deflections measures the power being taken up in the inductive part. It has been suggested by MM. Blondlot and Curie that the difference can be obtained at once by one reading by means of an electrometer with two pairs of quadrants and two needles on the same shaft but insulated from each other, one needle connected to the point B, and the other to the point C, and both pairs of quadrants connected to A and B. It has been shown, however, by Dr. J. Hopkinson, and also by Profs. Ayrton and Perry, that it is not safe to assume that *any* quadrant electrometer, however made, follows this theoretical law. It is possible to devise one that does, but we must not assume without justification by experiment that any kind of deflectional quadrant electrometer can be so used. Messrs. Ayrton, Perry and Sumpner have devised a form shown in Fig. 57, which does obey the theoretical law.* They have pointed out that the quadrant electro-

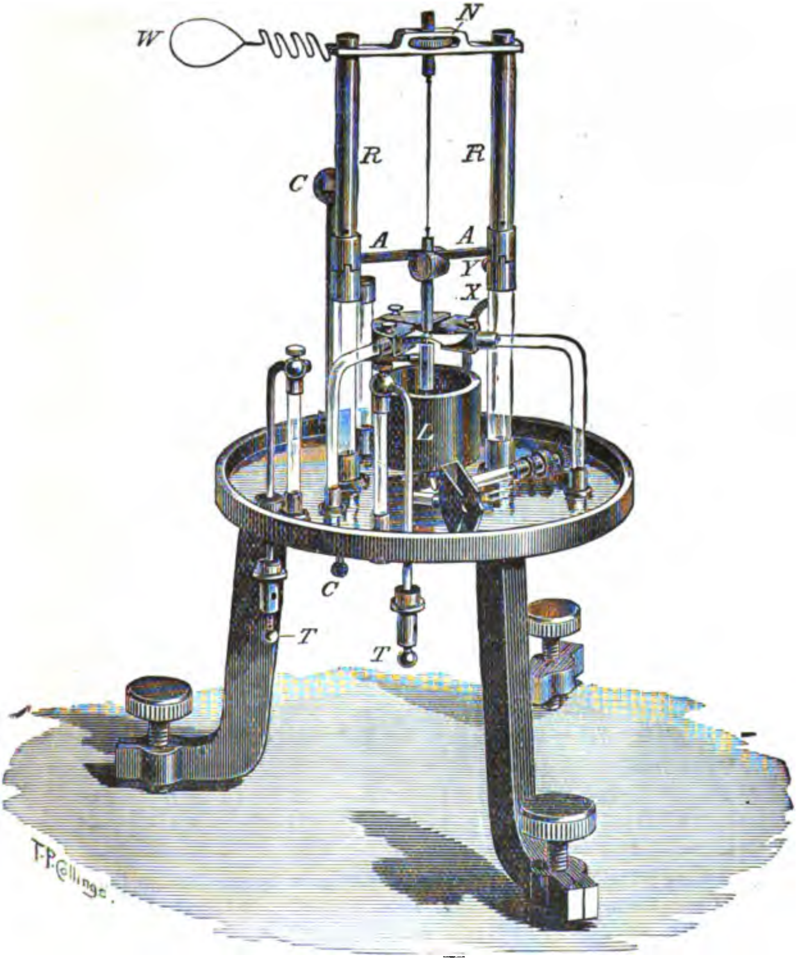

FIG. 57.—Ayrton, Perry, and Sumpner Quadrant Electrometer.

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* See *Transactions of the Royal Society of London*, Vol. 182 (1891), p. 519. "Quadrant Electrometers."

meter, if used to measure the mean power given to an inductive circuit, does not give correct results unless the quadrants are in one special position. The experimentalist has therefore to be on his guard against this source of error. It will be noticed, however, that assuming the electrometer to obey this law, the instruments can be used to measure mean power without any restrictions as to the form of the current curve or any special law of variation of the instantaneous values of the current during the phase.

The mean power given to an inductive circuit can, however, be accurately measured by means of three voltmeters, which may be quadrant electrometers used idiostatically by means of a method simultaneously suggested by Messrs. Swinburne, Ayrton, and Sumpner.* It is as follows:—Let A B be an inductive circuit, say, the primary circuit of a transformer, in which it is desired to measure the electrical power taken up. A B may be the primary circuit of a transformer, with loaded or unloaded secondary circuit, or the circuit of a choking coil. In series with it must be placed a non-inductive resistance, B C, whose ohmic resistance, R, shall be approximately equal to the impedance of the inductive circuit. Three electrostatic voltmeters or quadrant electrometers used idiostatically† are joined up as shown in Fig. 58. Let v_1, v_2, v_3, be the instantaneous values of the potentials at the points A, B, and C. Then we have always

$$(v_1 - v_3) = (v_1 - v_2) + (v_2 - v_3).$$

Hence,

$$(v_1 - v_3)^2 = (v_1 - v_2)^2 + (v_2 - v_3)^2 + 2\,(v_1 - v_2)\,(v_2 - v_3).$$

Therefore,

$$(v_1 - v_2)\,\frac{(v_2 - v_3)}{R} = \frac{1}{2R}\left\{(v_1 - v_3)^2 - (v_1 - v_2)^2 - (v_2 - v_3)^2\right\}.$$

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* *See* "The Measurement of the Power given by any Electric Current to any Circuit," by Prof. Ayrton and Dr. Sumpner; *Proc. Royal Soc.*, London, Vol. XLIX., 1891, p. 424.

† If the needle of a quadrant electrometer is joined to one pair of quadrants, then a difference of potential made between this one pair of quadrants and the other pair, the needle is deflected and the deflection is proportional to the square of the difference of potential between the two sets of quadrants. The electrometer so used is said to be joined up *idiostatically*, and makes use of no other charge than its own.

If we examine these terms we shall see that the term on the left-hand side is the product of the instantaneous value of the potential difference (P.D.) at the ends of the inductive resistance and of the current flowing through it. It is, therefore, the instantaneous value of the power given to that circuit. The three terms on the right-hand side are the P.D.'s respectively acting on the three electrometers. Call these P.D.'s, V_1, V_2, and V_3; that is, let $v_1 - v_3 = V_1$, $v_1 - v_2 = V_2$, and $v_2 - v_3 = V_3$. Then we get as an expression for the mean power W, being taken up in the inductive circuit the equation

$$W = \frac{1}{2R}\{V_1^2 - V_2^2 - V_3^2\}.$$

The expression is entirely independent of any assumptions as to the form of the curves of current or electromotive force.

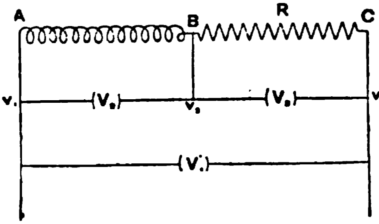

FIG. 58.

In putting this method into practice, however, several difficulties occur. In the first place, as we are taking the differences of squares of quantities, a very small error in the quantities themselves may make a very much larger percentage error in the resulting measure of the power. To get the best result V_2 should be about equal to V_3, and thus V_1 must be about double either of them. In testing a transformer by this method we have to provide, therefore, an excess of primary pressure; that is to say, to test the power given to the primary of a transformer which normally requires 2,000 volts on its primary terminals to work it, we have to provide 4,000 volts; and this is not always convenient. In practically carrying out this method to test a transformer we may proceed thus: Provide two transformers T_1 and T_2 with low-tension coils arranged in parallel, and high-tension coils in series, so as to give on the high-tension side double the working primary volts required for the transformer T to be tested. In series with T arrange a non-inductive resistance R, which may consist of incandescence lamps joined up in series, and arrange four electrostatic voltmeters V_1, V_2, V_3 and V_4, as shown in Fig. 59. Also put an ammeter A, capable of measuring with great accuracy the current flowing through the lamps. Let the instruments be joined up as shown in the diagram. Then the mean watts or mean power W given to the primary circuit of the transformer T is given by the expression

$$W = \frac{A}{2V_3}\{(V_1 + V_4)^2 - V_2^2 - V_3^2\},$$

where V_1, V_2, V_3, V_4 are the instrumental readings of the several voltmeters. We leave the proof of this as an exercise to the student.

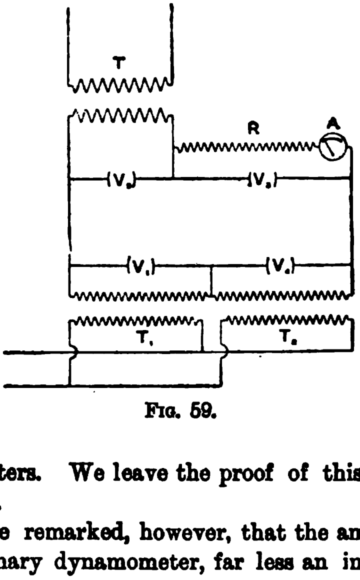

FIG. 59.

It should be remarked, however, that the ammeter A must not be an ordinary dynamometer, far less an instrument with any iron in it. It should consist of a coil of German silver, or platinoid, wire wound non-inductively, and having a suitable electrostatic voltmeter connected to its two extremities. In order to get the best results the actual values of the four voltmeter readings should be as nearly as possible equal to each other.

In applying this four-voltmeter method to measure the power given to the primary circuit of ordinary transformers worked say at 1,000 or 2,000 volts, it is essential to employ an accurate electrostatic voltmeter. It is impossible to employ for this method any electro-dynamic or electro-magnetic voltmeter. Mr. Swinburne has designed a form of electrostatic voltmeter very well adapted for this work. It is shown in Fig. 60. It consists of four semicircular brass boxes, like flat pill boxes cut in half vertically. These are insulated from each other and arranged in pairs in two tiers. A vertical metallic stem or axis carries two semicircular aluminium discs, so fixed to the stem on opposite sides and above one another that when the axis is held suspended vertically in the centre of the instrument and is free to rotate, one-half disc of aluminium is held centrally, half in one box and half in the other on the same level; whilst the other half disc is similarly situated with respect to the pair of boxes on the lower level. Hence the arrangement is a condenser of which the needle, or axis with half discs attached, forms one plate and the metal boxes the other. Alternate boxes are connected together, so that if we call A and B the boxes on the top tier and A′ and B′ those below, then A is connected to B′ and A′ to B. One pair, say A + B′, are also connected to the needle which is carried by a phosphor-bronze

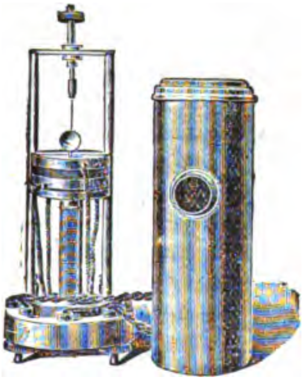

FIG. 60.—Swinburne Electrostatic Torsion Voltmeter.

wire. When one needle and one pair of boxes are brought to a different potential to the other pair of boxes, the needle is angularly displaced. By means of a torsion head the suspending wire is twisted and the needle brought back to its original symmetrical position. To effect this adjustment easily a mirror is attached to the needle stem. With care and proper precautions such an instrument is very sensitive and will indicate a variation of one-quarter per cent. in a voltage of 2,000 or 2,400. The author has employed four such instruments in experiments on transformer efficiencies with satisfactory results. The only objection is, that not being inspectional instruments they require a torsion head to be moved before a reading can be taken.

Ammeter or Current-reading Methods.—The foregoing voltmeter methods are in many cases inapplicable; because to carry them out with success it is necessary to be able to command a primary voltage of about double that which is normally required to actuate the transformer under test, and this is not always possible. Hence the author suggested (see *The Electrician*, May 8, 1891,) a method in which amperemeters are employed, and in which no extra volts are required, but in which additional current is demanded. Let *a b* be, as before, the inductive circuit in which the power taken up is to be measured (*see* Fig. 62). Place three ampere-meters suitable for measuring alternating currents, or three low-resistance dynamometers, at A_1, A_2, and A_3, and let r be a non-inductive resistance which may consist of incandescence lamps. If *ab* is the primary circuit of a transformer, apply electromotive force to the leads until the normal voltage is obtained. Let the

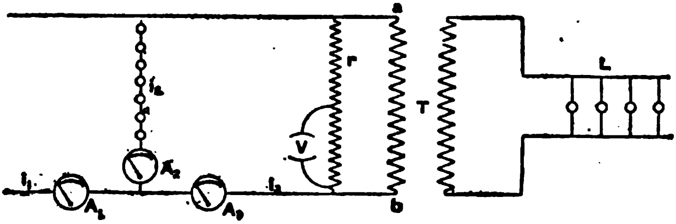

FIG. 62.

currents at any instant through A$_1$, A$_2$, and A$_3$, be i_1, i_2, i_3; then we have always

$$i_1 = i_2 + i_3.$$

Hence,

$$i_1^2 = i_2^2 + i_3^2 + 2\,i_2\,i_3.$$

But if v is the potential difference between the leads at that instant then $r i_2 = v$, *provided that* the ampere-meter A$_2$ is practically non-inductive, such an instrument, for instance, as the twisted strip ammeter of Profs. Ayrton and Perry. Hence we have

$$i_1^2 = i_2^2 + i_3^2 + 2 i_3 \frac{v}{r},$$

or

$$i_3 v = \frac{r}{2}(i_1^2 - i_2^2 - i_3^2).$$

But $i_3 v$ is the instantaneous value of the power being given to *a b*.

Hence if we take mean values throughout a period and call I$_1$, I$_2$, I$_3$, the $\sqrt{\text{mean}^2}$ values of the currents and W the mean power given to *a b*, we have by integration through a period

$$W = \frac{r}{2}\left\{ \frac{1}{T}\int_0^T i_1^2\,dt - \frac{1}{T}\int_0^T i_2^2\,dt - \frac{1}{T}\int_0^T i_3^2\,dt \right\}$$

$$= \frac{r}{2}\left\{ I_1^2 - I^2_2 - I_3^2 \right\}$$

The power in watts given to the circuit *a b* is therefore measured in terms of the readings of the three ammeters.

In carrying this method out in practice it is best to proceed as follows :—Suppose it is desired to measure the power taken up in the primary circuit of a transformer which works at 2,000 volts. Arrange a transformer to provide this voltage. Let T be the transformer under test. Provide a non-inductive resistance, consisting of fine platinoid wire, so wound on a frame as to keep cool. Let this wire be of such a size and resistance that it can be kept joined across the mains without sensible heating. Let r be the resistance of this wire. Connect a multicellular (Kelvin) electrostatic voltmeter to the ends of such a fraction of this wire that it reads at the best part of the scale. Suppose it reads well at 100 volts, then join its terminals to two points separated by one-twentieth part of r. Let V be this voltmeter so joined. Then by reading V and knowing the ratio of the parts into which the resistance is so divided, we know at any instant the potential difference between the primary leads. Then insert across the mains a series of, say, 20 incandescence lamps of 100 volts, so as to form a non-inductive resistance L, and arrange three amperemeters as shown, viz.: A_1, A_2, A_3. Let A_2 be capable of being short-circuited, and let it be a very low-resistance dynamometer, or an Ayrton and Perry twisted strip amperemeter of negligible inductance. Begin by taking the readings of the three amperemeters and of the voltmeter, and calculate the resistance of the lamps from the quotient of the volts at the extremity of the series of lamps as given by V, and the current through them as given by A_2. From this and the three ammeter readings calculate by the above formula the power taken up in the fine-wire non-inductive resistance r, and see if the result agrees with that calculated by dividing the square of the potential difference between its ends by its measured resistance. If this is the case we can be tolerably confident that the instrumental readings are correct. Next join on the primary terminals of the transformer to the ends of the resistance r and take a fresh set of readings. From these we can calculate the total power taken up in the resistance r and in the transformer, and hence that in the latter becomes known. The advantage of having the non-inductive fine-wire circuit is that it enables us to check the readings by measuring a known power, and also that it increases the reading of the ammeter A_3, which might otherwise be very small.. The most favourable case for accuracy presents itself when the current through A_2 is about equal to that through A_3. In this method as in the three-voltmeter method, since the formula contains a function which is the difference of squares of observed quantities, a relatively small error in the instrumental readings will make a much larger percentage error in the final result. For further discussions on these methods of current and voltmeter measurement of alternating-current power, we must refer the reader to a Paper by Prof. Ayrton and Dr. Sumpner, entitled "Alternate Current and Potential Difference Analogues in the Methods of measuring Power." (*Phil. Mag.*, August, 1891, p. 204.)

It will be seen that whilst the voltmeter methods are dependent upon the possibility of obtaining a primary pressure at best, nearly double the working primary electromotive force of the transformer, these currents or ammeter methods are dependent upon the possibility of obtaining increased currents over and above that required by the primary of the transformer. Both methods have the disadvantage of necessitating a waste of power in a dead resistance, which waste of power is approximately equal under most favourable conditions for accuracy to the power being measured. The methods are, therefore, hardly applicable to such a case as that of measuring the power being sent out from an alternating-current station into the primary circuits of a large number of transformers. It would be then generally impracticable to produce the conditions favourable to accuracy, and such instrumental readings as could be obtained would be affected by errors which would totally vitiate the calculated results.

Wattmeter Methods.—In most of the methods previously described for measuring the power given by alternating currents to an inductive circuit a collection of instruments is required, and in most of them also a non-inductive resistance is employed as an addition to the circuit in which the power is to be measured. Generally speaking, when such a non-inductive circuit is employed, it has to be of such a character that it is possible to waste in it a power approximately equal to, or even much greater than, the power given to the circuit under test. Outside of the laboratory, therefore, all these methods are not always convenient, and often entirely impracticable. Take the case of an alternating-current station supplying current to distributed transformers. It is not possible to obtain the proper conditions necessary to employ any of the voltmeter, ammeter, or dynamometer methods described above with success. Neither is it possible to obtain double the working pressure necessary for the application of the three-voltmeter method, nor is it practicable to obtain a non-inductive resistance sufficiently proportioned to be capable of wasting an amount of power proper to apply any of the other similar methods under conditions in which the results of observation would be likely to give figures of adequate accuracy to deduce the true power given out.

There is one instrument, however, which does not necessitate in its use as a power-meter any such proportional expenditure of power. This instrument is the dynamometer with a thick and a thin wire coil. The theory of this instrument when employed to measure alternating current power has been discussed in Vol. I., Chap. III., § 17. It is there shown that if one coil of a dynamometer is inserted in series with an inductive circuit in which the power taken up is to be measured, and if the other coil is made a shunt across the terminals of this circuit, then the couple required to hold the movable circuit in a position in which its plane is at right angles to the fixed circuit is strictly proportional to the power taken up in the inductive circuit only under two conditions:—(i.) when the time constant of the inductive circuit is equal to that of the shunt circuit of the dynamometer, and (ii.) when the time constant of this last circuit is absolutely zero. It is almost impossible to realise the first condition, and hence the utilisation of the dynamometer as a direct wattmeter without the use of any additional instrument is dependent upon the possibility of making the time constant of the shunt circuit of the wattmeter practically zero. This result can be obtained by making the movable coil of the dynamometer of a very few turns of wire, and placing in series with this outside the instrument a truly non-inductive resistance of no sensible capacity and of appropriate magnitude. If the fixed coil is placed in series with the circuit to be tested, then under these circumstances the power given by an alternating current to that circuit can be determined from the wattmeter readings, using a constant for the instrument which has been previously determined by experiments with continuous currents.

It has been shown, however (Vol. I., Chap. III., § 20), that if the time-constant of the fine-wire circuit is not truly zero a correcting factor must be applied to the instrumental constant determined by experiments with continuous currents in order to make it applicable to alternating-current measurements on inductive circuits; and the magnitude of that factor is dependent upon the time-constant of the dynamometer shunt circuit, and that of the circuit under test. Also that factor contains a term which is a product of these time-constants, and which is not zero unless the time-constant of the shunt circuit is absolutely zero. The shunt circuit of the dynamometer may possess either a certain small amount of self-induction or a small amount of capacity, and either of these may therefore bestow upon the shunt circuit such a positive or negative equivalent inductance that when the product of its time-constant and that of the circuit under test is taken the product is not a small quantity which can be neglected. It is not safe, therefore, to assume, without making special tests, whether any proposed arrangement of shunt circuit in a dynamometer wattmeter has a time-constant so nearly zero that its finite value introduces no errors into the measurements proposed to be made with it. If this precaution is not taken, the reading of the wattmeter, when taken on an inductive circuit, will not give the true power when interpreted by means of an instrumental constant determined by the help of continuous currents. Each particular wattmeter needs, therefore, to have critical and particular attention bestowed upon it before it can be employed to measure alternating current power. One method by which this can be accomplished is to compare the readings, given by the wattmeter in question, of the power taken up in an inductive circuit, say in the primary circuit of a transformer on open secondary circuit with the readings given by a method of acknowledged accuracy, viz., the three-voltmeter method. The proper conditions must be secured for obtaining the highest accuracy. It is important, therefore, to know under what conditions we can obtain with the three-voltmeter method the most accurate results. We shall therefore in explaining this quote literally the paragraph from the paper by Prof. Ayrton and Dr. Sumpner in which they discuss this important matter.*

Taking the arrangement figured on page 555, let V_1^2 stand for the mean of the squares of the instantaneous values during the period of the potential difference between the ends of the inductive resistance under test V_2^2 for the same quantity over the non-inductive resistance in series with it, and V^2 for the same over all the two circuits together. Then if W is the watt power taken up in the inductive circuit, and r is the ohmic resistance of the non-inductive circuit, then we have seen that

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* "*On the Measurement of the Power given by any Electric Current to any Circuit*" (Ayrton and Sumpner), *Proc. Roy. Soc.*, London, Vol. 49, p. 434, 1891.

$$W = \frac{1}{2r}(V^2 - V_1^2 - V_2^2);$$

therefore, $$dW = \frac{1}{r}(V\,dV - V_1\,dV_1 - V_2\,dV_2),$$

where dV_1, dV_2, dV are the errors made in the estimation of the three potential differences.

Let
$$\begin{aligned} dV &= \pm eV, \\ dV_1 &= \pm eV_1, \\ dV_2 &= \pm eV_2, \end{aligned}$$

where e is a small fraction, *i.e.*, let the errors in each measurement be the same per cent. of the quantity measured.

The most probable value of $(dW)^2$ is

$$\frac{1}{r^2}(V^2 e^2 V^2 + V_1^2 e V_1^2 + V_2^2 e^2 V_2^2),$$

so that $$\left(\frac{dW}{W}\right)^2 = 4e^2 \frac{V^4 + V_1^4 + V_2^4}{(V^2 - V_1^2 - V_2^2)^2} \quad . \quad . \quad . \quad (1)$$

Let the non-inductive resistance have such a value that

$$V_2 = xV_1 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

We wish to find the value of x which will make $\frac{dW}{W}$ a minimum. Let the potentials vary harmonically, and let ϕ be the angle of lag between the potential difference of the terminals of the inductive circuit, and that of the non-inductive circuit. Since

$$v = v_1 + v_2,$$

these being instantaneous values, we have

$$V^2 = V_1^2 + V_2^2 + 2V_1V_2\cos\phi \quad . \quad . \quad . \quad (3)$$

Eliminating V, V_1, and V_2 between equations (1), (2), and (3), we have

$$\left(\frac{dW}{W}\right)^2 = 4e^2 \frac{(1 + x^2 - 2x\cos\phi)^2 + 1 + x^4}{4x^2\cos^2\phi}. \quad . \quad . \quad (4)$$

Now $\cos\phi$ is independent of x, hence to find out what value of x makes dW/W a minimum we differentiate the numerator of (4) and equate to zero, and we find that $x = 1$ makes $\frac{dW}{W}$ a minimum. Hence the arrangement which will give the greatest possible accuracy in the measurement of W is that in which

$V_2 = V_1$, or in which the potential drop over the inductive circuit is equal to the potential drop over the non-inductive circuit.

In (4) put $x=1$; we have then

$$\frac{dW}{W} = 2e \frac{\sqrt{2+4(1+\cos\phi)^2}}{2\cos\phi},$$

or

$$\frac{dW}{We} = \frac{\sqrt{2+4(1+\cos\phi)^2}}{\cos\phi}. \quad . \quad . \quad . \quad . \quad (5)$$

But $\frac{dW}{We}$ is the ratio between the percentage error made in measuring the power, and the percentage error made in measuring one of the potential differences. If we were applying this method to measure the power taken up in the primary circuit of a closed magnetic circuit transformer with open secondary circuit, the value of $\cos\phi$ would be about ·75. If we put $\cos\phi = \frac{3}{4}$ in (5) we find that $\frac{dW}{We} = 5$. Hence an error of 1 per cent. in measuring each of the alternating potential differences would involve an error of at least 5 per cent. in the measurement of the power, and to get the power correct to one per cent. we must be certain that the voltmeter readings are correct to within a quarter per cent. Since $\cos\phi$ is more nearly zero when measuring the power taken up at no load in the primary of an open magnetic circuit transformer, say a Hedgehog transformer, it follows that it is more difficult to measure with a given percentage accuracy the inductive power taken up in a circuit, the power factor of which is small, than the power taken up in a closed magnetic circuit transformer in which the power factor is large.

Returning to the wattmeter measurement, we may say that the above-described three-voltmeter method must be applied with the necessary care to check the readings of a dynamometer wattmeter before these last can be depended upon. Experiments by the author have shown that very considerable errors may be introduced in wattmeter measurements by small but sensible capacity in the shunt circuit of the wattmeter.

The sum and substance of the foregoing discussion is that the wattmeter can be made to be an accurate instrument for the measurement of the power given to an inductive circuit, but the user of such instrument should take some care to assure himself that the wattmeter shunt circuit is truly non-inductive, or that its time-constant is sufficiently small not to affect the accuracy of the measurements proposed to be made, by reason either of self-induction or capacity in this shunt circuit.

Graphic and Integrating Methods.—In discussing the work of Prof. Ryan on "Transformer Indicator Diagrams," we have seen that when the primary electromotive force and current curves of a transformer have been drawn, we can, by multiplication of the corresponding instantaneous values, draw a power curve showing the power given to the primary circuit at every instant. By taking the mean value of the ordinates of this power curve during one complete period, we obtain the mean power given to the primary circuit. This method, though very laborious, is probably as accurate as any of the above-described methods. It is, however, of very limited application, and not at all suitable for general use.

§ 15. General Relations of Efficiency and Size of Transformers.—Foregoing remarks will have made it evident to the reader that the designing of transformers is a matter which is to a considerable degree a tentative one, and that very small changes in the proportion of the various parts will often considerably affect the result. Let us assume, however, that a constructor has before him a transformer of good design, and which is highly efficient. He wants to know how far this form is a guide to making larger or smaller transformers of the same kind. Mr. Kapp has pointed out* that if we take a given transformer and make every part twice as large whilst retaining the induction density constant, we shall make the output of the transformer 32 times as great, for we retain the same number of coils and turns in each, and hence the total induction is four times as great as before. The electromotive force is also, therefore, four times as great. The resistance of the coils has, however, been reduced to one-half, because the section has been increased to four times and the length doubled. Hence, if we allow the same copper loss, we can now allow a current which will be eight times its former value. Hence the output of the transformer is increased 32 times, because the current is increased eight times and the electromotive force four times; accordingly the output is increased as the fifth power of the increase of the linear dimensions. The weight of the transformer will only be increased as the cube of the increase of the linear dimensions. It is therefore seen that large transformers are more economical to build than small ones, and that they have a greater output per unit of volume. Mr. Kapp, however, points out that since the surface is relatively smaller, in the case of the large transformer, it is not possible to take full advantage of this increase of output in practice. It is found that for every watt lost in the transformer in core or coils together, a cooling surface of from three to four square inches must be provided. In large transformers ventilation becomes of great importance, and as the failure of a large transformer is more serious than the failure of a small one, it is essential that the temperature shall be kept down to a point at which the insulation is not permanently injured. As far as regards mere temperature effect on the metals, we have seen that it is advantageous for the iron to run to as hot as possible, provided the permeability is not much diminished, and that, similarly, the copper ought to be kept cool. One of the difficulties which has to be faced in the system of distributed transformers is that of finding suitably ventilated places for transformers. In a properly designed substation, fans can be used to circulate air or pumps to circulate oil round the transformers, and so a steady removal of heat can be effected, thereby enabling us to take the full advantage of large size. It is hardly too much to say that when properly constructed large substation transformers are employed in well-designed substations the efficiency of distribution of such a transformer system could be made quite equal to that of any low-pressure direct-current system, and be kept certainly above 90 per cent. This is not possible when small distributed transformers are employed. In this case the efficiency of distribution may fall as low as 50 per cent. The term "efficiency of distribution" is here used to denote that fraction expressed as a per cent. of the whole of the electrical energy sent out in one year from the generating station which is delivered and sold to the consumers.

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* "Professional Papers of the Corps of Royal Engineers," 1892, Vol. XVIII., Paper III., p. 41.

CHAPTER V.

OTHER PRACTICAL USES OF TRANSFORMERS.

§ 1. **Electrical Welding.**—The application of the transformer for purposes other than electric lighting has led to the development of inventions in which the inductive transformation of electric energy plays an important part. In none of these is the striking peculiarity of the transformer better brought out than in its utilisation in electric welding. In electric welding we see the principle of the transformation of electric energy pressed, as it were, to its utmost limit, in that currents of enormous strength but exceedingly low voltage are generated by currents of small strength and, relatively, very high voltage. We owe this youngest of the electrical arts to Prof. Elihu Thomson, who made known the processes in 1886 or 1887. This novel way of utilising electric energy depends on the simple fact that if a very large electric current is passed through a conductor which is severed, but which has its severed ends pressed together, enough heat will be generated at the junction to raise to incandescence the ends, and fuse them together. The peculiarity of this process of electric welding is that not only the hitherto so-called weldable metals, but almost all others, can be similarly treated. Hitherto the metals which have been welded with facility by the ordinary methods of furnace heating and subsequent hammering have been wrought or soft iron, steel, platinum, pure gold, and a few others; but such metals as cast iron, brass, gunmetal, bronze, German silver, zinc, tin, lead, aluminium, and other alloys have not hitherto been found capable of being so welded; and even in the case of copper, which softens rapidly by heating, the welding together of two pieces has been found impracticable, by reason of the great rapidity with which heated copper oxidises. Much less has it been found practicable to weld pieces of different metals together by ordinary processes; and, even in the case of iron, very small pieces can scarcely be welded in the ordinary way, on account of the rapidity with which the small mass cools, thus reducing the temperature of it below the welding heat.

All this, however, has been changed by the invention of the interesting process of electric welding. Deferring for the moment further details, the process of electric welding, apart from the special apparatus, may be thus described. Suppose, for instance, that two rods of brass or iron are to be welded end to end, the ends to be joined are made slightly oblique or convex. The rods are then grasped respectively in the jaws of two powerful clamps, fixed to a bench in such a way that the axes of the rods are in the same straight line. One of the clamps is fixed, while the other can be made to move parallel to the axis of the rod, by means of a screw. The two clamps are insulated from one another, and are made the terminals of an electric circuit, which may be the secondary circuit of a particular kind of transformer or that of the armature of a dynamo, or a secondary battery, or any generator for furnishing a very large current.

The arrangement for furnishing current being given, the operation of electric welding is comparatively simple. The movable clamp is screwed forward until the rods just touch one another, and a small quantity of powdered borax is sprinkled at the junction to remove the oxide. The current is then switched on and increased in strength until the metal at the junction becomes sufficiently hot for the two pieces to fuse together. The movable clamp is meanwhile screwed forward so as to squeeze the two rods into perfect contact, the temperature being all the while maintained, if need be, by increasing the current. When the joint is perfect, the piece is removed from the clamps and bent or otherwise hammered to the required shape on an anvil, while still hot. The portion of the rods heated is quite short, most of the heat being generated at the junction, initially because of the slightest resistance of the contact in the first place, and afterwards because of the relatively high resistance of the heated part of the rod after the junction has become complete. Should the weld, on examination, prove to be faulty, the specimen may be again put into the clamps and re-heated; the bad weld would in most cases have sufficiently high resistance to localize the heat.

It will be seen that this method has immense advantages for light work. Where electrical power is available, the clamping appliances can be fixed to a bench in any part of the workshop, and the operation is clean, exact, and expeditious. Another great advantage is, that almost any metal can be welded by this means. Metals most commonly used to illustrate the process are cast iron, steel, wrought brass and copper, all of which weld perfectly. So complete is the junction that the specimens when tested afterwards are generally found to break at other places than at the weld. In welding large bars the currents that are required are considerable, but as the current is maintained only for a short time, the actual power consumed is not great. For instance, the current required to effect a weld between ½-inch steel rods is about 450 amperes, but a somewhat smaller current suffices to maintain the welding heat after it has once been obtained.

The process of electric welding is, therefore, seen to be essentially dependent upon the high resistance produced at a contact of two metals, and subsequently upon the high resistance of a hot metal, combined with the application of pressure of the two ends when the welding temperature is obtained.

It is obvious that special means are necessary to obtain the immense currents requisite for effecting electric welding. The only two processes which have been found practicable for generating these currents are dependent upon the use either of a low-resistance dynamo or of a transformer with a specially constructed low-resistance secondary coil. The first method, employing a dynamo, is called the "direct type of welding," but has not such an extensive application as that process in which the transformer is employed. In Fig. 1 is shown a dynamo adapted for direct welding, as constructed by the Thomson-Houston Company. On a table above the dynamo are seen the jaws or clamps in which the rods to be welded are placed, and through which junction the current from the dynamo is passed. By far the most convenient processes are those which employ an induction coil or transformer, because by these appliances the requisite large current can be very easily obtained. In welding a rod of steel rather less than 1in. in diameter, it is roughly estimated that a current of 20,000 amperes is required, and in making larger welds, momentary currents up to 50,000 amperes are required. It must be borne in mind, however, that the electromotive force of this large current is very small,—at most, one or two volts between the clamps,—and, accordingly, the power taken up is kept within reasonable limits. In Fig. 2 is shown one of the earliest forms of electric welding transformers. It consists of an induction coil, having a core of iron wire about 12in. long and 2½in. in

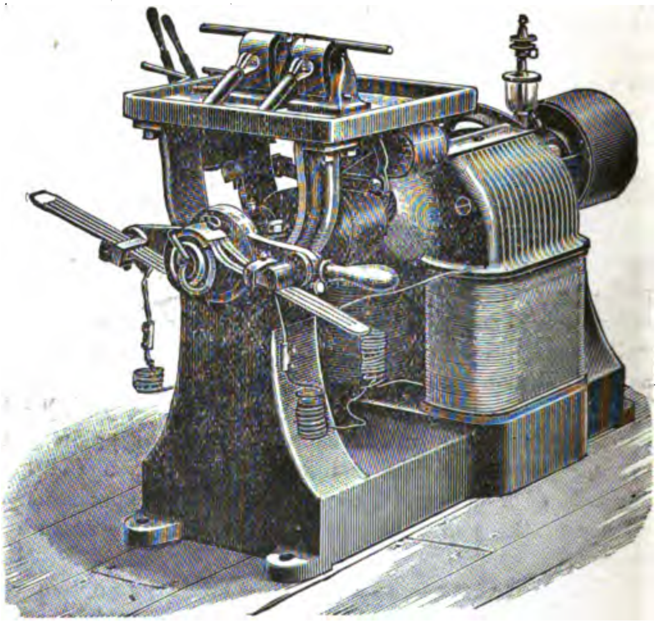

FIG. 1.—Thomson Welding Dynamo.

diameter, around which is wound a coil of primary wire intended to be traversed by the current from the alternating-current machine, under an electromotive force of 200 or 300 volts. The secondary circuit is composed of 64 wires, No. 10 gauge, bound together, and passing only eight times round the core. The ends of this stranded secondary circuit are bolted down to fixed copper plates, upon which are the clamps, formed of massive blocks of copper, intended to hold the pieces to be welded. One of these clamps is fixed and the other slides upon guides on its own bed-plate, being drawn towards the fixed clamp by means of a screw. A cam is arranged to be turned so as to separate the clamping appliance by forcing back the movable block and holding it so during the placing of the rods in the clamps.

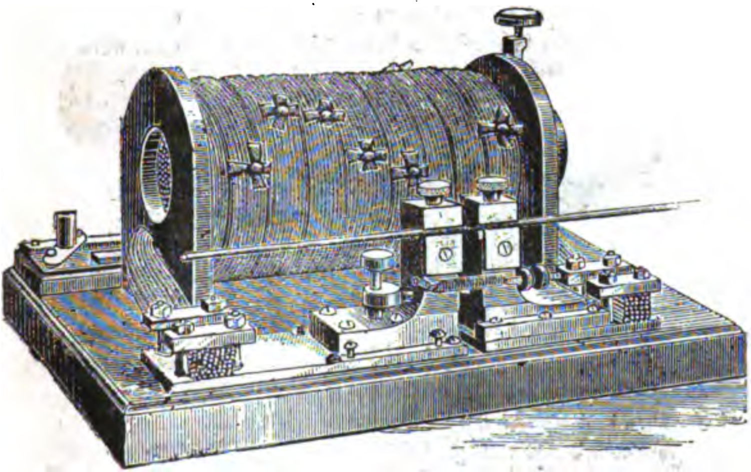

Fig. 2.—Early Form of Welding Transformer.

It will thus be seen that the secondary circuit of the transformer consists of a secondary coil, having an exceedingly low resistance, probably not more than 0·00015 of an ohm. When the alternating current is passed through the primary circuit, it generates in this low resistance secondary an enormous current, having a very low electromotive force. On the starting of this current the larger part of the resistance of the secondary circuit exists just at the point of contact of the metal rods placed in the clamps, and hence at this place nearly the whole of the energy of the secondary circuit is expended. As the ends of the rods heat up to brilliant incandescence, they are pressed together by means of a spring between the clamps, thus forcing them into union and effecting a complete junction. The plan of the arrangement is shown in Fig. 3. As it is impossible to place a switch in the secondary circuit, the current is made or broken by a switch, W, placed in the primary circuit of the transformer.

It is obvious that if we were using a perfect conductor of electricity placed between the jaws of such an electrical welding transformer, we could have no electrical heating whatever, because the conductor, having no resistance, would not dissipate any of the electric energy of the current passing through it, and therefore no heat would be produced. It is equally obvious that if we employed a substance absolutely non-conducting, no current would pass through it, and we could not therefore heat it. Fortunately, both iron and steel occupy an intermediate position in respect of their conducting power. At the ordinary temperature of 60° Fahrenheit, a piece of wrought iron 1ft. long and 1sq. in. in section would need half a volt to drive

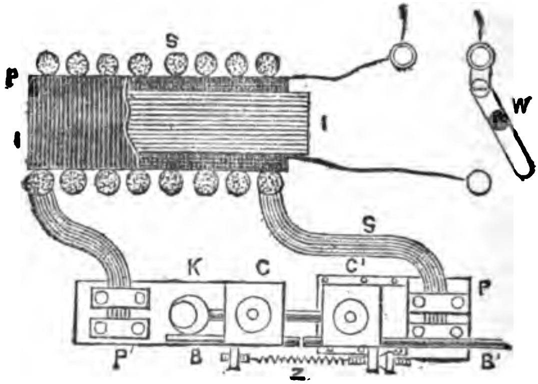

Fig. 3.

10,000 amperes through it; in doing this 3,700 foot-pounds of electric energy would be dissipated in a second of time.*

If we used a similar length and area of German silver we should in the same time dissipate rather more than double that amount of energy, namely, 7,700lbs. A similar length and area of silver would therefore dissipate only 515lbs. of electric energy. It is extremely likely that at the temperature at which welding can be performed, the electric resistance of iron to the flow of the electric current is increased to at least eleven-fold that which it has at the freezing point, because the welding temperature is about 3,000° Fahrenheit. Assuming, however, the electric resistance to be increased by only eleven times that which it has when the iron is cold, it follows that a piece of iron one foot long and one square inch in section would under these circumstances dissipate in one second 40,700 foot-pounds of electric energy. Accordingly, as the metal becomes heated in the process of welding, even after the actual joint is made, the hot metal continues to dissipate at a great rate the energy which is spent in it.

A more recent welding appliance, devised by Professor Elihu Thomson, is shown in Fig. 4. It consists of a transformer having a secondary circuit formed of a single massive loop of copper, S, laid parallel with a primary coil, P, the two being wrapped over with iron wire so as to form a transformer. The ends of the secondary circuit terminate in massive clamps in which the rods to be welded are placed, these ends of the secondary circuit can be drawn together by means of a screw or separated by a spring. In this transformer the resistance of a secondary circuit is not more than ·00003 of an ohm, and the electromotive force set up in the secondary circuit is about 2 volts. A current of little over 20 amperes and 600 volts applied to the primary will produce in the secondary circuit a current of nearly 12,000 amperes, with an electromotive force of 1 volt. Provision is made for cutting off the circuit from the primary circuit by means of a switch. Transformers constructed on this principle are called "welding transformers," and they have been developed into numerous forms applicable

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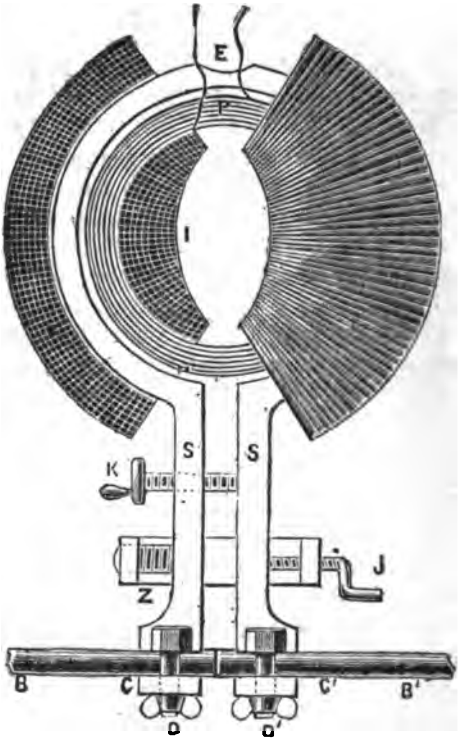
* *See* Sir Frederick Bramwell on "Welding by Electricity," Proceedings of the Royal Institution of Great Britain, Vol. XIII., p. 190.



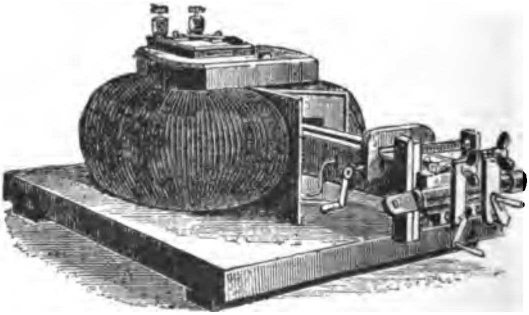


FIG. 4.—Welding Transformer.

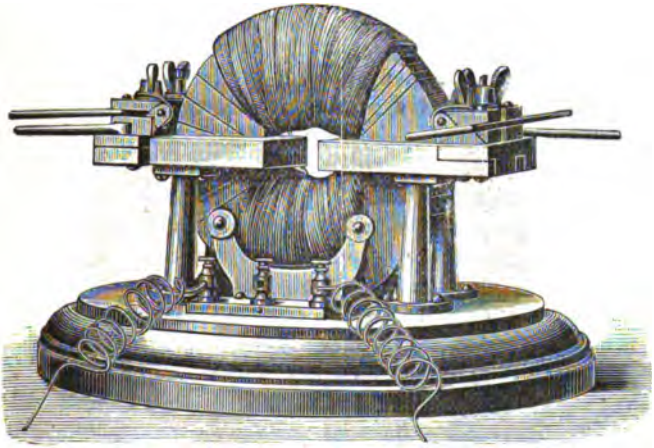


FIG. 5.—Thomson Welding Transformer.

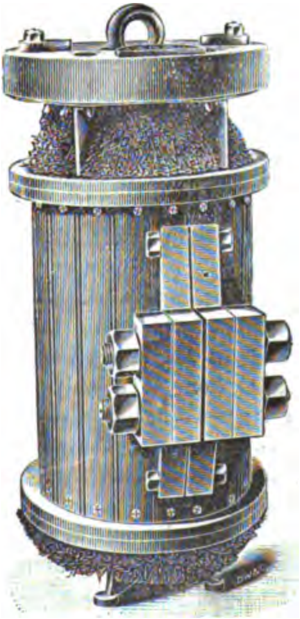


FIG. 6.—" Hedgehog " Welding Transformer.

to the immense variety of purposes for which electric welding has been found useful. Fig. 5 shows a similar form of welding transformer, having two very low resistance secondary circuits of different sizes. Fig. 6 shows a sketch of a "Hedgehog" transformer with very low resistance secondary circuit, intended for welding purposes.

§ 2. **Applications of Electric Welding.**—It has been found that with a properly designed transformer and properly proportioned clamps, there is almost no limit to the application of electric welding in the constructive arts. Merely to mention a few of these applications, the following may be enumerated as instances of what can be done. Lengthening of screw taps, drills, augers and reamers to any amount required, by the insertion of a new piece of steel in the length, the new welds being in all respects just as strong as the neighbouring metal; similarly it has been applied in mending chisels and punches by giving them new edges, welded to the old body; lengthening screw bolts by welding sections of new bar between the head of the bolt and the screw, or shortening them by cutting out sections and re-uniting the head and the body; welding new drills and reamers to the shanks of old worn-out tools; renewing of worn-out centres of lathes, or making new tools by welding a piece of fine steel for forming the cutting edge on to a piece of iron or less valuable steel, forming the shank or body of the tool. In addition to these appliances, large work, such as the butt-welding of metal taps or pipes up to 6in. in diameter, making continuous piping of steel, iron or brass by welding into one length shorter pieces, even up to such lengths as 1,000ft., for bending into coils; making and repairing endless bands, as band saws, wheel tyres, barrel hoops, railway-carriage axles, &c. Not only is electric welding applicable to such large work, but also to the very delicate work of the jeweller's art, such as the welding of steel wires of less than $\frac{1}{200}$th of an inch in diameter. It is applied also in making links for chains.

It may seem at first sight difficult to understand how a ring can be electrically welded, but there is no mystery about it. In welding a ring of any kind, whether a wheel tyre or the link of a chain, the bar to be welded is first bent round approximately into the shape required for the ring or link, and the open ends are then placed in the clamps of the welding transformer. When the current is turned on the greater part of the current passes across the shorter distance, which is that contained between the clamps, and the greater resistance and greater self-induction of the longer length outside the clamps prevent anything more than a small fraction of the current passing through it. Moreover, it has been found possible, by the ingenious device of linking an iron loop or an iron ring with a ring to be welded, to increase the self-induction of that part of the ring to be welded which is outside the clamps, so that practically no current passes at all by that route, but it all goes across the junction which is held between the clamps.

By the process of electric welding feats can be performed which would be absolutely impossible to achieve by ordinary hand-welding; such, for instance, as heating a rivet in its place and welding it up *in situ*, also welding lengths of lead piping together so perfectly that not even a burr is left on the outside of the pipe.

Passing on, then, to a more detailed description of the process of welding we may say that the welding plant consists in the first place of a motive power, generally a steam engine, driving a dynamo, which can furnish an alternating current. These dynamos, called "welding dynamos" as made by the Thomson-Houston Company, are all similar in form, but vary in size and dimensions. The field-magnets, projecting inwards from a frame, have four or six pole-pieces made of separate plates of iron securely bolted together and to the frame, the coils being fixed on in the ordinary way. The armature is generally a pole armature, that is to say, the core has projections on which the armature coils are wound. The alternating current is taken off the collector rings in the ordinary way. The dynamos are made self-oiling, and either self or separately exciting. As the dynamos are only required to furnish current for short periods and not constantly, their output is much greater than it would otherwise be for the same size of machine for continuous work. These dynamos are generally wound to furnish current at an electromotive force of 300 volts, and give a current making 100 complete alternations a second, or 6,000 per minute. The alternating current so provided is brought to the primary circuit of the welding transformer, which may be placed at any reasonable distance from the machine. Close to the welding transformer is placed a switch for closing the primary circuit. This is generally actuated by means of a treadle, so that the primary circuit is only closed at the instant and during the time that the operator's foot is placed upon this treadle. In this way accidents are prevented which might occur if the primary switch was left permanently closed. In addition to this switch there is a re-active coil (see Chapter II., page 269), the object of which is to control the strength of the primary current by the movement of the handle of the re-active coil. The operator has thus perfect control over the strength of the primary current, and can close the primary circuit by one movement of the foot, and control the current strength by one movement of the hand.

In the construction of the welding transformer it is necessary to so design that the total cross section of copper in the primary and secondary circuits is about the same. The joints in the secondary circuit of the welding transformer must be made as massive as possible and have perfect contact; or else with the immense current circulating in the secondary circuits there would be great heating and waste of energy at any contact which was not perfect. The iron core of the welding transformer is formed of thin sheet-iron plates, bolted together. The primary circuit consists of coils put on to the core through an opening which is afterwards filled with a laminated block. The secondary circuit consists of a single massive copper tube or bar passing through the centre of the core and connected at the two ends with massive copper castings, supporting the welding clamps. This whole appliance is placed upon the proper base with a sort of table at the top, which supports the clamps and pressure devices. The clamps are usually made with one clamp kept stationary during welding and one movable clamp. The pressure is obtained by a screw, worked by a worm wheel and ratchet.

One of the first questions asked by a person who sees electric welding for the first time is, how much power does it take to effect a weld? There is considerable difficulty in measuring the power taken up in such a low-resistance circuit, but the result of tests has shown that the average power consumed in welding a ½in. bar of iron is about 6½ H.P. if welded in 10 seconds; a 1in. round iron rod requires 12 H.P. when welded in 40 seconds; a 1½in. round iron rod requires 18 H.P. and welded in 90 seconds. A rough estimate of the efficiency of the apparatus showed that from 60 to 70 per cent. of the power supplied by the engine was taken up in the weld. The time taken in making the weld is a very important factor, as the quicker the weld is made the greater is the power consumed. If a piece of 1in. round iron is welded in 40 seconds it takes 12 H.P., it would require about twice the power to effect a weld in half the time; but, on the other hand, if the weld is made too quickly, the metal is burned at the end in contact, and if it is made too slowly the machine and the clamps are over heated, and much energy is lost by radiation. There is, therefore, for every particular kind of weld a proper speed at which it must be made to get the best results. For 1in. round iron rod it is estimated that about 5,000 amperes passing for 20 seconds effects a weld; for a 2in. round iron rod about 20,000 amperes passing for 80 seconds effects a weld.

Success in the application of this process of electric welding to the welding of different metals and objects is found to depend greatly upon the proper disposition of the objects to be welded in the clamps. The less the projection of the piece beyond the clamps the less is the power used, as the resistance through the bar is lessened; but if the pieces project too little the clamps become heated to a high temperature, and are burned or heated more than necessary. If a too great projection is given to the ends of the bars to be welded, then much power may be lost by radiation, and a longer length of bar may be heated than is required. In welding together different metals, such as brass and iron, or aluminium and copper, it is found necessary to make the pieces project from the clamps to different degrees, and a certain skill and acquaintance with the process has to be acquired before the best results can be obtained. For heavy work it is found necessary to keep the clamps cool, by having them made hollow and circulating water through them.

In welding together a very easily fusible metal such as aluminium or lead to a more refractory metal, such as brass or copper, the amount by which each bar projects from the clamps is an important matter in securing an efficient weld, because the clamps carry away the heat by conduction; and, therefore, if the rod of most easily fusible metal is so set in the clamps that it only projects a little way, it is possible to manage matters in such a fashion that the two rods come to just the proper temperature to effect the weld—the temperature of the most easily fusible metal being prevented from rising to an excessive point by the great conductivity of the clamp in which it is inserted.

Amongst the metals that have been welded by this process are gold, platinum, silver, copper, aluminium, bismuth, cobalt, antimony, zinc, tin, lead, iron, nickel, manganese and magnesium. Amongst the alloys welded are the different kinds of bronze—phosphor bronze, aluminium bronze and solid bronze, malleable and cast iron, German silver, lead and tin. Amongst the combinations welded are:—Copper to brass, brass to iron, brass to German silver, German silver to iron, cast iron to wrought iron, lead to tin, tin to zinc, brass to tin, gold to silver, silver to platinum. Prof. Elihu Thomson has welded a bar $\frac{3}{8}$ths of an inch in diameter, made up of the following nine metals welded together in short lengths, in the following order:—Copper, brass, iron, German silver, brass, tin, zinc, tin, lead. A similar bar was sent to the Paris Exhibition of 1889.

With regard to the tests of strength of the so welded metals, the report of tests made with the Rich testing machine shows that wrought-iron may be welded so as to possess the same tensile strength at the joint as the unwelded bar. When a perfect weld is made, the fracture is usually within the welded portion of the bar caused by the stock being annealed at that section. If the welded bar breaks at the weld, it is no sign that the weld was a poor one, so long as the tensile strength is equal to that of the unwelded bar. If the weld by an ordinary blacksmith's process stands 70 to 75 per cent. of the original stock it is called excellent; but in the electric weld as much as 85 per cent. is reached with the burr removed. Hammering the weld lightly at the welding heat gives it more strength, 95 per cent. or even 100 per cent. being then reached. Wrought-iron bar has a tensile strength of about 50,000lb. per square inch; Norway iron bar about 60,000lb. per square inch. The tensile strength of mild steel is from

60 to 80,000lb. per square inch. The tensile strength of tool steel may be 120,000lb. per square inch, or even more. The strength of a tool-steel weld is greatly improved by light hammering while at a welding heat, if properly done. The welding heat of steel is far below that of iron, so that in welding steel more pressure is required to effect the weld than for iron, because the steel is not so plastic as the iron. The temperature range between the burning point and the non-welding point is rather small, so that some skill is required to effect a good weld. The higher kinds of cast-steel require considerable care in welding. With regard to the welding of copper, tensile tests of welded copper show as high as 90 to 98 per cent. of the annealed stock. The tensile strength of annealed copper is about 32,000lb. per square inch. Wrought brass is welded without difficulty. The percentage of tensile strength obtained is very high. The tensile strength of annealed brass is about 47,000lb. per square inch. A very good joint can be made between brass and iron.

With regard to the manufacture of chains, they are usually made with a double weld in each link. Chains have been electrically welded and tested in sizes from one-sixteenth of an inch wire to one inch round iron. Chains made from one-sixteenth of an inch wire stand a strain of 260lb.; chains made from one-eighth of an inch bar iron stand a strain of 790lb.

The variety of uses to which this method of electrical welding applies is almost unlimited and too numerous to mention. Probably no invention covers such a broad field of work and such possibilities. Briefly speaking, they may be comprised within such limits as welding of rods and bars from the finest wire up to 6in. in diameter, joining bars of different shape and section, welding railway rails, welding conductors for electrical purposes, making continuous piping for carrying gas, oil pipes, boiler tubes, &c., making chains and link work from the smallest jewellers' work to a heavy ships' cable, all of which great variety of work is capable of being dealt with, with ease and celerity.

The result of some tests made at Kirkaldy's and recorded by Sir Frederick Bramwell are as follows:—80 welds were made in round iron bars 1⅛in. in diameter, they took an average of 2¼ minutes each to make, which was roughly devoted as follows:—clamping the iron and heating up to red heat each portion, 26 seconds; full heat to taking out of jaws, 11 seconds; work on anvil, 15 seconds; re-putting in to full heat 21 seconds; full heat to taking out again, 10 seconds; re-taking out to completion, 32 seconds; completion to putting in next piece, 20 seconds; making a total of 135 seconds. As a comparison with this, two ordinary blacksmiths were put to make welds in similar bars in the ordinary manner. They made 44 welds in three hours and little over, or practically the same time as was taken in making the 80 welds electrically. Then all the welds were sent to Kirkaldy's to be tested, and he tested one half of them with the following results:

Average tensile strength of bars, 52,642lb. per square inch.

Average strength of those which broke at the weld when welded electrically, 48,215lb.

Average strength of those which broke at the weld with the welds made by hand, 46,899lb.

From these tests we have a right to say that these electrically-made welds gave at least an equal tensile strength to scarf welds done by hand. These tests indicate also clearly the fact that the strength at the weld is about 90 per cent. of the strength of the unbroken bar.

One very practical application of electric welding is in joining up lengths of iron telegraph wire. For the convenience of Telegraph Companies these wires are put up in coils measuring each exactly half a mile in length. In order to obtain this length, it has been generally the custom to make up the proper length, when necessary, by splicing with a common telegraph joint after the wire has been galvanised. This gave a large and cumbrous joint; and the electrical welded joint is in every way preferable, so much so, that if the joint has the burr taken down by an emery wheel, it is impossible afterwards to detect where the wire has been joined. Similarly, with regard to steel cables for use in mines. The steel cable can be electrically welded in such a manner that the tensile strength of the joint is approximately equal to that of the unbroken cable, and yet the cable will be in no degree thickened up at the joint. The most varied field for electric welding work has been found in welding together the different parts of bicycle wheels and frames. The material in this case is soft steel or Norway iron; the crescent tyres of bicycle wheels can be easily electrically welded, and the different parts of the frames put together without any rivets. In the United States a large variety of manufacturing firms have adopted electrical welding for their special needs, such as chain making, and the making of continuous pipes. In addition to the actual process of jointing together two lengths of a bar, the electrical welding transformer can be most usefully employed in "upsetting" iron bars. For instance, if a collar is required upon a steel shaft, the shaft is placed in the jaws of the welder and brought to a bright welding heat. The clamps are then squeezed together, thus "upsetting" the bar, forming a bulge on it, which can afterwards be turned down into a collar.

The processes of electrical welding have thrown light upon the actual production and nature of burnt steel. By forcing the heat in welding, no matter if rapidly, the effect of burning can be produced as thoroughly as by means of a fire. This shows that the burning of steel is not a mere oxidation, but a molecular re-arrangement, and by carefully averaging the heating the metal can be restored to its original condition.

A large variety of tests of the strength of electrical welding joints have been made by Prof. E. A. Dolbear, with a testing machine, at the United States Arsenal at Watertown; and from these tests evidence was clearly obtained that the tensile strength of the bars so electrically welded was approximately as great at the joints as at any other part of the bar. Prof. Dolbear's opinion is as follows:—

"I have made nearly 100 tests of the tensile strength of electrically welding bars of iron, steel, and other metals. The results were of such a character that I can state positively that, with the Thomson welding process, it is possible to weld both wrought iron and steel so that the weld is as strong as the same cross section in any other part of the bar. The appearance of the fracture is fibrous for iron, and generally granular for steel, the strength of this granular steel being in some samples as high as 125,000lb. per square inch. I had a number of bars welded by an expert blacksmith and a number of similar ones by the electrical process, with the result that the electrically welded bars were stronger at the joint than those by the ordinary process. The bars were of various sizes up to 1½in. for iron and ¾ of an inch for octagon steel."

§ 3. **Conclusion.**—There are several other applications of induction coils in telegraphy and telephony which might be described, did space permit. We may, in conclusion, make very brief reference to their employment in the phonopore of Mr. Langdon-Davies. In his system of induction telegraphy Mr. Langdon-Davies employs an induction coil made in a peculiar manner, which constitutes it partly a coil and partly a condenser. In constructing this coil, a single layer of insulated copper wire is first put upon a divided iron core, and its ends brought out. A second layer is so laid, and so on for, say, twenty layers. The ends of these circuits are then joined so that the whole forms one primary circuit composed of twenty circuits in parallel. This forms the primary circuit of the coil. Mr. Langdon-Davies finds that such a primary causes less spark at the contact breaker than one which consists of a single circuit of wire. The secondary circuit of the coil is composed of two insulated wires—one end of each wire is permanently insulated, and the other ends form the terminals of the secondary circuit. It will thus be seen that the secondary circuit is not a complete metallic circuit. One end of this incomplete secondary circuit is connected to earth, and the other to the line. When a rapid series of interruptions are made in the primary current, secondary currents are set up in this secondary circuit by reason of the combined capacity and mutual induction of the two secondary circuits with respect to one another and to the primary circuit. These short secondary currents are employed to actuate a particular form of receiver. A secondary circuit so constructed of two separate wires is, however, perfectly non-conducting towards steady currents or currents of such duration as are employed in ordinary telegraphy. Accordingly, when such a phonoporic induction coil is employed in parallel with an ordinary telegraphic relay having considerable self-induction, currents of sensible duration, such as telegraphic currents, pass through the relay but not through the phonopore, but rapidly intermittent or oscillatory currents coming in from the line pass through the phonopore secondary coil but do not actuate the relay. Hence a system of induction telegraphy can be superimposed on the same line wire as that on which ordinary telegraphic work is being carried on. In telephonic work the currents sent into the line are secondary currents produced from a small induction coil in the transmitter. The variation in the strength of the primary currents in this induction coil produced by the variation of resistance of a loose contact in the primary circuit is made to generate secondary currents, which follow in strength these variations in the primary current.

These and other special applications of the induction coil are to be found fully described in works specially devoted to telephony and telegraphy. We have confined ourselves in the present treatise more particularly to the consideration of those applications of the induction coil in electrical engineering in which it is usually spoken of as a transformer, and in which it is employed to effect the inductive transformation of considerable amounts of electrical energy.

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